A Human-based Study of Hand-arm Vibration Exposure Limits for Construction Workers

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Abstract

In many developed countries and cities, the construction industry, which is a major economic pillar, is expanding at a rapid pace. In this context, the use of construction machines and vibrating tools for various construction activities is indispensable. With the increasing use of handheld vibrating equipment, construction workers are exposed to hand-arm vibration (HAV), which is a serious occupational risk for those who work with vibrating tools and machinery that cause vibration damage to the fingers, hands and arms. Long-term and chronic exposure to HAV, it may induce hand-arm vibration syndrome (HAVS), resulting in vascular, neurological and musculoskeletal disorders. HAVS causes permanent and irreversible damage, leading to a high level of disability and work impairment. Due to its severity, a pilot study of HAV is revisited in accordance with the existing exposure points system from the U.K.'s Health and Safety Executive. Two important factors are considered, namely worker's age and local climate (e.g., temperature and humidity). A simple idea is proposed to optimize the applicability of the exposure points system to different age groups and climates. The findings of this human-based study may be used as a practical reference for policymakers and contractors.

Keywords: Hand-arm vibration, Vibration exposure limits, Occupational Safety, Climate effect, Age

1 Introduction

In densely populated cities, many large-scale building, infrastructure and demolition projects are currently aimed at sustainable urban development. Because of hectic construction activities, hand-arm vibration syndrome (HAVS) is a prevalent occupational disorder that is caused by prolonged exposure to hand-arm vibration (HAV), in which high-frequency vibrations are transmitted to the human hand-arm system through handheld power-driven machines[1]. This medical condition mainly develops due to repeated injury to small nerves and capillaries, but it

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depends on vibration magnitude, frequency and exposure duration[2]. Many occupational groups face the possibility of developing this disease after long-term use of vibrating machines and tools. Workers using high-impact percussive tools in building and construction work experience high levels of exposure to both vibration and shock. The long-term exposure of hands and arms to vigorous vibration and shock can induce serious vascular, neurological and musculoskeletal disorders, resulting in permanent damage and disability[3,4]. In addition to its effects on health and safety, this work-related occupational disorder may result in loss of productivity, increases in insurance premiums, numerous medical claims and project delays[5].

Different estimated percentages/numbers of workers suffering from HAVS in various workplaces/construction situations have been found in the literature. In Australia, the statutory agency Safe Work Australia reported that approximately 24% of workers experienced exposure to vibration at their workplaces[6]. In Canada, 72,000 to 140,000 prevalent cases of HAVS have been estimated[2]. In China, the prevalence of HAVS among construction workers using various vibrating tools has ranged from 2.5% to 82.8%[7,8]. In the Netherlands, estimated 20,000 workers are exposed to HAV as a result of working with percussive pneumatic tools[9]. Furthermore, the U.K.'s Medical Research Council conducted a survey that estimated more than 280,000 HAVS sufferers[10]. The U.S. Bureau of Labour Statistics estimated that approximately 2.5 million workers are regularly exposed to high HAV levels at work[11]. According to the Hong Kong Census and Statistics Department[12], approximately 110,000 construction workers are employed in various disciplines. Most of these workers are frequently exposed to the use of high-impact percussive tools, such as breakers, saws and drills.

Confronted with the detrimental effects of HAVS, the ISO5349-1 standard[13] regulates the measurement and evaluation of human exposure to HAV. The U.K.'s Health and Safety Executive provides a system of exposure points to evaluate the exposure limit of workers when using handheld vibrating tools. The typical HAV exposure standards for the action and limit values, respectively, are 2.5 m/s^2 and 5.0 m/s^2 on a daily 8-hour basis. These two values were established in accordance with the 10% prevalence of vibration white finger (VWF) among the exposed population with reference to previous studies[14]. This exposure points system is simple and provides a clear guideline for workers and contractors. However, previous studies have reflected that the existing system must be further improved by considering more factors that affect HAVS. As such, we suggest including the effects of age and climate into the existing system.

The effect of a cold climate on HAVS has long been studied. For example, Yu et al.[15] suggested that a cold climate could be a causative factor in HAVS. Bovenzi et al.[16] found that even without HAV exposure, the prevalence of VWF was higher during cold winter climates. Burström et al.[17] advocated that the risk of suffering from VWF would increase if exposed to HAV in a cold climate. Some studies have also pointed out that cold climate may trigger VWF, such that workers should wear protective gloves to reduce the hazard risk[18,19]. Inaba and Mirbod[20] also evaluated the effects of cold exposure on the musculoskeletal system among construction electricians, including the vibration exposure problem.

It is also noteworthy that construction activities are energy-intensive tasks for the development of work-related occupational disorders, especially in hot and humid climates. Many studies have examined the effects of hot climates on construction workers from different perspectives. Su et al.[21] investigated the 8-hour time-weighted average vibration exposure in tropical environments. Devine[22] considered HAV exposure in warm climates. Bovenzi[23] conducted a comparison study between observed VWF outcomes in epidemiological studies of vibration exposed worker groups. Furthermore, Chan et al.[24] showed that heat stress was a dominant factor seriously affecting the productivity of workers and inducing a higher safety risk. More recently, Yi et al.[25] investigated the heat stress of workers in a hot and humid summer work environment and examined the effectiveness of a newly designed hybrid cooling vest for construction workers.

The tolerance of workers to HAV is not limited to climate effects. The age of workers is also a confounding factor in many studies[8,26,27]. In current practice, identical limits are imposed on both younger and older workers. However, classifying workers from different age groups under different HAV exposure limits may protect them better. The preceding research has been carried out to study the relationship between the age of workers and HAVS. For instance, Hopcroft and Skinner[28] pointed out that workers of different ages experienced various vibration effects, as transmissibility changed with age. Fung and Tam[29] investigated whether the physical conditions of older workers would decline and ultimately affect their work. Burström et al.[17] analyzed the odds ratio (OR) for the prevalence of VWF among different HAV-exposed age groups.

We conducted a pilot study to revisit the existing HAV exposure points system by including two important factors (i.e., age and climate). Policymakers and contractors can use the findings of this study as a practical reference that identifies the importance of protecting and improving the working environment of construction workers.

2 Hand-Arm Vibration Exposure Standards

2.1 Regulations on Hand-Arm Exposure in Different Countries

The U.K.'s Health and Safety Executive lists the vibration magnitude of conventional machines causing HAV in workers, as shown in Table 1. It shows that HAV is affected by the vibration magnitude (termed "acceleration") of hand-arm vibrating tools. Indeed, the development of HVAS (e.g., musculoskeletal damage) depends on time duration, frequency and acceleration amplitude. In Table 2, the acceleration and exposure duration related to developing HAVS as a result of using various vibrating tools in China are extracted from the reference[7]. The statistics from both countries show that the rock drill produces intensive HAV in workers. Following the rock drill, the U.K. ranks the hammer as a more harmful tool, whereas China ranks the saw and grinder higher than the hammer.

Table 1 Vibration magnitudes of conventional machines that cause HAV[30]

Type of Tool	75^{th} Percentile Acceleration a_{hv} (m/s^2)	"Trigger Time" to Reach Action Value
Rammers	38	< 3 min
Rock Drills	20	< 10 min
Demolition Hammers	18	< 10 min
Road Breakers	17	10 min
Impact Drills	16	< 15 min
Saws	16	< 15 min
Chipping Hammers (metalworking, foundries)	15	< 15 min
Vibratory Rammers	12	20 min
Impact Wrenches	9	40 min

Sanders	9	40 min
Chainsaws	7	1 h
Grinders	7	1 h
Needle Scalers	7	1 h
Die Grinders	6	1 h 20 min
Clearing Saws	5	2 h

Table 2 Summary of epidemiological studies of HAVS in China[7]

Tool types and number of users	Prevalence of VWF (%)	Acceleration Level (a_{hv}, *rms*)	Duration of exposure (year)
Rock Drill (29)	82.8	51.6 $a_{hv(4)}$	5.8 (mean)
Rock Drill (97)	60.8	-	2 – 14
Rock Drill (153)	54.9	-	4.8 (mean)
Rock Drill (81)	49.4	14.8 $a_{hv(4)}$	2 – 18
Rock Drill (112)	45.5	-	-
Rock Drill (137)	43.3	16.5 $a_{hv(4)}$	1 – 12
Rock Drill (245)	41.4	30.8 $a_{hv(4)}$	7.7 (mean)
Chain Saw (266)	41.0	-	6.2 (mean)
Riveter, Grinder (93)	35.0	10.0 $a_{hv(4)}$	1 – 21
Chain Saw	31.9	18.6 $a_{hv(4)}$	2 – 12
Chipping Hammer Grinder (159)	23.3	2.3 – 51.6 $a_{hv(4)}$	-
Pedestal Grinder (600)	22.0	-	5.6 (mean)
Rock Drill (165)	13.3	25.5	7.2 (mean)
Rock Drill (673)	12.6	11.4 – 91.9	1 – 21
Mixing Hammer (297)	7.4	19.6	1 – 9
Breaker and Chipping Hammer (483)	2.7	13.6 $a_{hv(4)}$	1 – 16
Chipping Hammer Riveter (266)	2.5	14 – 22	1 – 8

$a_{hv(4)}$ = Energy equivalent frequency-weighted cacceleration for a period of 4 hours; *rms* = Root mean square, m/s^2.

In terms of HAV exposure, Table 3 shows the relevant requirements adopted by different countries, such as Australia, Canada, China, those in the European Union and others. The typical HAV exposure standards for the action and limit values, respectively, are 2.5 m/s^2 and 5.0 m/s^2 on a daily 8-hour basis. In Japan, the same standard values are also adopted. However, the Japan Society for Occupational Health[31,32] also recommended the occupational exposure limit for hand-arm vibration using the total value of frequency-weighted rms acceleration of 2.8 m/s^2 for 480 mins (8 hrs).

Table 3 HAV exposure standards in different countries

Country/Union	Requirements
The United Kingdom[19]	• Exposure action value: 2.5 m/s^2 A(8) • Exposure limit value: 5.0 m/s^2 A(8)
The United States[33]	• Not over 5.0 m/s^2 A(8)
The European Union[34]	• Exposure action value: 2.5 m/s^2 A(8) • Exposure limit value: 5.0 m/s^2 A(8)
Australia[6]	• Exposure action value: 2.5 m/s^2 A(8) • Exposure limit value: 5.0 m/s^2 A(8)
China[7,35]	• Not over 5.0 m/s^2 A(4)
Canada[33]	• Often follows the limits and guidelines recommended by the American Conference of Governmental Industrial Hygienists (ACGIH) - Not over 5.0 m/s^2 A(8)
Japan[36,37]	• Adopted the EU Directive 2002/44/EC[34] • See Note 2 Below
New Zealand[38]	• Exposure action value: 2.5 m/s^2 A(8) • Exposure limit value: 5.0 m/s^2 A(8)

Note 1: A(8) or A(4) refer to the daily vibration exposure for workers under vibration effects.

Note 2: The Japan Society for Occupational Health[31,32] also recommended the occupational exposure limit for hand-arm vibration using the total value of frequency-weighted rms acceleration of 2.8 m/s^2 for 480 mins.

To systematically assess the HAV exposure, the U.K.'s Health and Safety Executive[19] introduced an exposure points system that evaluates the HAV using the following equation:

$$n = \left(\frac{a_{hv}}{2.5}\right)^2 \times \frac{t}{8} \times 100 \qquad (1)$$

where n is the number of exposure points (corrected to the nearest integer in the U.K.'s HAV exposure points system), a_{hv} (in m/s^2) is the vibration magnitude that results from the superposition of vibration along three orthogonal directions in contact with the hand and t (in hour) is the daily duration of exposure to vibration magnitude a_{hv}. Besides, the allowable daily vibration exposure $A(8)$ (in m/s^2) is also related to the vibration magnitude, a_{hv}, as follows[39]:

$$A(8) = a_{hv}\sqrt{\frac{T}{T_0}} \tag{2}$$

where T (in hour) is the duration of exposure to the vibration magnitude and T_0 is the reference duration of 8 hours.

By substituting the HAV exposure action value (i.e., 2.5 m/s^2) and limit value (i.e., 5.0 m/s^2) into Eq. (1), 100 and 400 points, respectively, are obtained as the action and limit values using the HAV exposure points system. The HAV exposure points system table is given by the U.K.'s Health and Safety Executive, as shown in Table 4.

Table 4 HAV exposure points system of the Health and Safety Executive[19]

Vibration magnitude (m/s²)	15m	30m	1h	2h	3h	4h	5h	6h	8h	10h
40	800									
30	450	900								
25	315	625	1250							
20	200	400	800							
19	180	360	720	1450						
18	160	325	650	1300						
17	145	290	580	1150						
16	130	255	510	1000						
15	115	225	450	900	1350					
14	98	195	390	785	1200					
13	85	170	340	675	1000	1350				
12	72	145	290	575	865	1150	1450			
11	61	120	242	485	725	970	1200	1450		
10	50	100	200	400	600	800	1000	1200		
9	41	81	160	325	485	650	810	970	1300	
8	32	64	130	255	385	510	640	770	1000	1200
7	25	49	98	195	295	390	490	590	785	865
6	18	36	72	145	215	290	360	430	575	720
5.5	15	30	61	120	180	240	305	365	485	605
5	13	25	50	100	150	200	250	300	400	500
4.5	10	20	41	81	120	160	205	245	325	405
4	8	16	32	64	96	130	160	190	255	320
3.5	6	12	25	49	74	98	125	145	195	245
3	5	9	18	36	54	72	90	110	145	180
2.5	3	6	13	25	38	50	63	75	100	125
2	2	4	8	16	24	32	40	48	64	80
1.5	1	2	5	9	14	18	23	27	36	45
1	1	1	2	4	6	8	10	12	16	20
	Daily Exposure Time									

2.2 Limitation of the Existing System

Upon initial inspection, it appears that any locations can follow the U.K.'s HAV exposure points system directly due to its systematic structure and ease of application. However, it may not be appropriate to directly apply the system in different regions. Two major reasons are explained using Hong Kong as a ***counter example***. In Hong

Kong, the official document "Guidance Notes on Health Hazards in Construction Work" issued by the Occupational Safety and Health Branch of the Labour Department[40] mentions that the vibration of equipment may induce disease of the fingers and hands causing permanent damage to the nerves and a loss of sense of touch and dexterity. However, no specific exposure points system is available locally.

Workers 50 years of age or above constitute approximately 50% of Hong Kong's construction worker population and approximately 30% of that of the U.K., as shown in Fig. 1[41] and Fig. 2[42]. The workers in the construction industry in Hong Kong are older than those in the U.K. Furthermore, it is critical to note that the situation in Hong Kong is anticipated to worsen in the next 10 years, as 25% of those between 40 and 49 years of age will turn 50 years of age or above, resulting in an even larger proportion of older construction workers. Due to the differences in the age groups of construction workers in the two countries, the U.K.'s HAV exposure points system cannot be applied directly to the Hong Kong context.

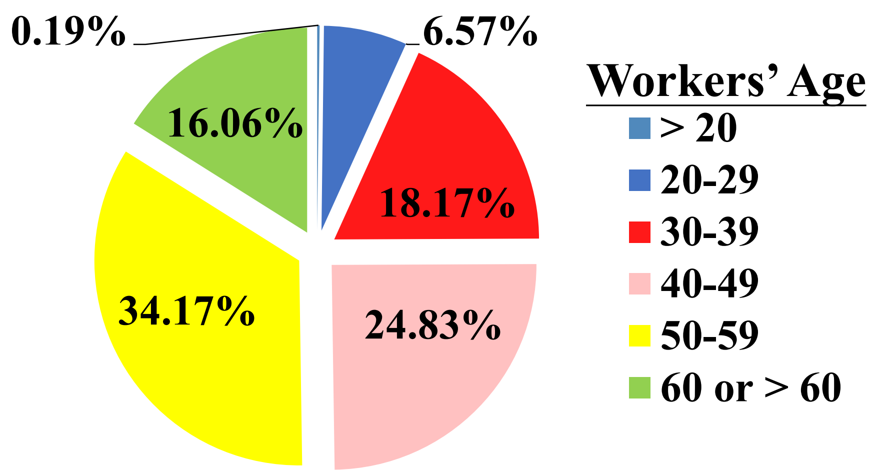

Fig. 1 Age composition of construction workers in Hong Kong[41].

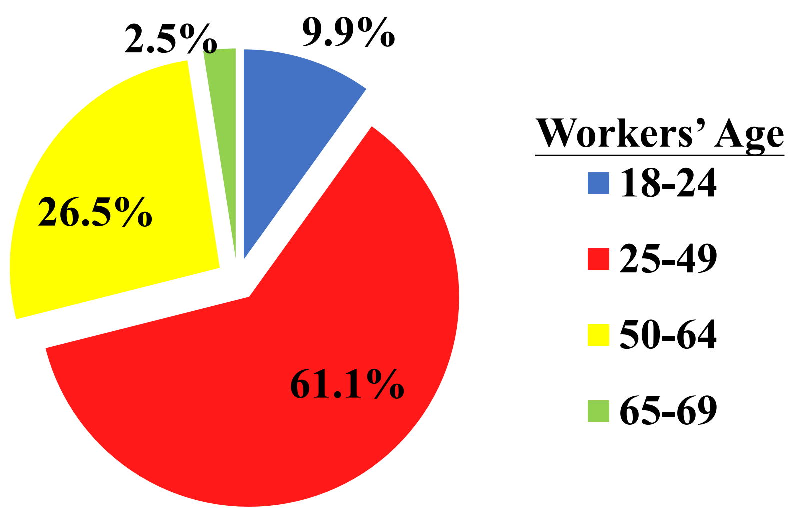

Fig. 2 Age composition of construction workers in the U.K.[42].

Table 5 shows the annual average temperature, rainfall, sunshine and humidity statistics of Hong Kong and the U.K. The annual average temperature, rainfall and sunshine levels in Hong Kong are higher than those in the U.K., whereas the U.K. is more humid than Hong Kong. Table 6 presents the summer weather details of both Hong Kong and the U.K. In summer, the overall temperature, rainfall, sunshine and humidity levels in Hong Kong are higher than those in the U.K. Hong Kong has higher temperatures (nearly double) and higher humidity levels than the U.K.

Table 5 Comparison of annual weather in Hong Kong and the U.K. (2001-2016)[43,44]

	Temperature (°C)	Rainfall (mm)	Sunshine (hrs)	Humidity (%)
HK Weather	23.5	2389.4	1835.7	78.4
UK Weather	9.2	1167.8	1425.3	82

Table 6 Comparison of summer weather in Hong Kong and the U.K. (2001-2016)[43,44]

	Temperature (°C)	Rainfall (mm)	Sunshine (hrs)	Humidity (%)
HK Weather	28.6	1269.7	529.5	81.5
UK Weather	14.7	266.9	501.8	79

Theoretically, using the U.K.'s HAV exposure points system in Hong Kong may help prevent HAVS. However, due to the differences between the two regions, the age of construction workers and climate effects should also be considered.

3 Modifications and Discussion of the Existing Hand-Arm Vibration Exposure Points System

Extensive standards have been established according to the relationship between the vibration magnitudes of handheld machines and HAV exposure time, without considering age or climate. For cities with aging population and unique climates, e.g., Hong Kong, the U.K.'s existing HAV exposure points system is not comprehensive enough for direct application. Therefore, we present a concept that integrates age and climate into the HAV exposure points system.

3.1 Implications of Age and Climate

Age is a factor affecting the prevalence of HAVS among construction workers[17]. To adjust the HAV exposure time of construction workers of different ages, age multipliers are assigned to respective age groups. Climate, in particular temperature and humidity, is another dominant factor affecting the perception of construction workers suffering from HAV exposure[18]. To adjust the acceptable HAV exposure time of construction workers, climate multipliers are adopted according to different climates. The following equation is proposed to calculate the HAV exposure points under the effects of age and climate:

$$n_{new} = n \times m_a \times m_c \quad (3)$$

where n is the number of HAV exposure points defined in Eq. (1), n_{new} is the newly calculated number of HAV exposure points, m_a is the age multiplier, and m_c is the climate multiplier. In this paper, we only discuss the effects of age and climate on the HAV exposure points system in the subsequent sections, other uncertain factors are not included.

3.2 Age Multiplier

In the present HAV exposure standard, the basic principle is that the longer handheld machines are used for, the greater the damage done to the human hand-arm system is. Hence, older construction workers experience more damage due to prolonged HAV exposure, making them a more vulnerable to HAVS. Another major concern for older construction workers is that their body structures, such as their bones, tissues, muscles and vascular system, are not as strong as those of younger construction workers[45]. Accordingly, older construction workers are more vulnerable to the harm done by long-term HAV exposure. As mentioned, construction workers who are 50 years of age or above constitute approximately 50% of the construction working population in Hong Kong. Therefore, when applying the U.K.'s HAV exposure points system in Hong Kong, the age of construction workers should be considered.

Table 7 shows the OR of construction workers suffering from VWF in various age groups under HAV exposure. These results were obtained from the investigation of more than 19,000 workers[17]. Generally, the older the workers are, the higher the ORs are. The OR for workers under 60 years of age increases from 1 to 1.98. This demonstrates a higher theoretical prevalence level of VWF among older workers. Nonetheless, it is noteworthy the OR of workers 60 years of age or above is slightly lower than that of workers between 50 and 59 years of age, with an OR of 1.94. This may be due to the healthy-worker effect[17,46], which indicates that they are relatively healthy for employment, resulting in lower mortality and morbidity rates than similar age groups in other industries.

Table 7 Odds Ratios (ORs) for the prevalence of VWF in various HAV-exposed age groups of construction workers[17]

Workers' Age	OR for HAV-exposed Workers
≤29	1.00
30-39	1.24
40-49	1.71
50-59	1.98
≥60	1.94

We suggest using the ORs listed in Table 7 as the age multipliers when applying the U.K.'s HAV exposure points system, as they delineate the difference of having HAVS in various age groups. Although the health status and body flexibility of construction workers in different countries are not the same, it is plausible that similar trends can be observed (i.e., the older the workers are, the higher the OR of HAV exposure is). Hence, we present the calculation approach using ORs. Studying the specific ORs of construction workers in different countries and regions is not in the scope of our research. Consider the following age multiplier:

$$m_a = p_o \tag{4}$$

where p_o is the OR of construction workers is a particular age group.

The mechanism of the above equation is that of older construction workers, who have more HAV exposure points than younger workers with the same exposure duration (except for the workers 60 years of age or above due to the healthy-worker effect)[17]. In this way, older construction workers reach the HAV exposure action value faster than younger workers do. This implies that older workers have a shorter allowable period during which to use vibrating tools than younger workers.

3.3 Climate Multiplier

Temperature and humidity contribute to the prevalence of HAVS among construction workers, especially in cold environments. The probability of getting VWF is higher in cold areas than in warm areas[15,18,47]. Hence, the existing U.K. standard protects workers in relatively cold climates, but not in hot and humid climates. Construction workers undeniably suffer from VWF more easily in colder climates. However, previous studies have revealed that hot and humid climates increase muscular fatigue in workers, which is one of the symptoms of HAV[48]. Therefore, hot and humid weather is also associated with HAVS. For this reason, the climate factor should be added to the U.K.'s HAV exposure points system when it is used in hot and humid regions.

Hong Kong is located in a sub-tropical region[49]. The average temperature and relative humidity, respectively, are 28.6°C and 81.5% in summer[43]. Notably, 38 days with a maximum temperature of 33°C and 4 consecutive days of temperatures higher than 35°C were recorded in 2016[43]. Moreover, the relative humidity in summer is high, with an average over 80%, which impedes construction workers by sweating[50]. Working in this hot and humid environment, in addition to an energy-demanding workload, construction workers are prone to exhaustion and muscular fatigue in summer[51]. Consequently, their working productivity in summer is lower than that in other seasons, as muscular fatigue is correlated with productivity[52-54]. Therefore, the deteriorating effect of HAVS on the health of workers can be related to the decrease in their working productivity. Hence, we suggest that the decline of working productivity can be used as the climate multiplier. The effect of climate on construction workers is quantified in Table 8, which shows the relationship between the climate, in terms of temperature and humidity, and the working productivity of construction workers. We define the climate multiplier as follows:

$$m_c = \frac{1}{p_w} \tag{5}$$

where p_w is the working productivity of workers under certain temperature and humidity effects (%). In Table 9, all the suggested climate multipliers under different temperature and humidity conditions are listed coresponding to Table 8.

Table 8 Relationship of temperature and humidity to working productivity (%)[52]

		Temperature (°C)												
		-23	-18	-12	-7	-1	4	10	16	21	27	32	38	43
Relative Humidity (%)	90	56	71	82	89	93	96	98	98	96	93	84	57	0
	80	57	73	84	91	95	98	100	100	98	95	87	68	15
	70	59	75	86	93	97	99	100	100	99	97	90	76	50
	60	60	76	87	94	98	100	100	100	100	98	93	80	57
	50	61	77	88	94	98	100	100	100	100	99	94	82	60
	40	62	78	88	94	98	100	100	100	100	99	94	84	63
	30	62	78	88	94	98	100	100	100	100	99	93	83	62
	20	62	78	88	94	98	100	100	100	100	99	93	82	61

To obtain a conservative climate multiplier for the existing HAV exposure points system during hot and humid working days, for example, a temperature of 32°C and relative humidity of 80%, the working productivity of 87% is taken from Table 8 and the climate multiplier becomes $m_c = 1/0.87 = 1.15$ (Table 9). In this case, a larger exposure point is generated in a hot and humid climate.

Table 9 Climate multiplier (m_c) at different temperature and humidity conditions

		Temperature (°C)												
		-23	-18	-12	-7	-1	4	10	16	21	27	32	38	43
Relative Humidity (%)	90	1.79	1.41	1.22	1.12	1.08	1.04	1.02	1.02	1.04	1.08	1.19	1.75	-
	80	1.75	1.37	1.19	1.10	1.05	1.02	1.00	1.00	1.02	1.05	1.15	1.47	6.67
	70	1.69	1.33	1.16	1.08	1.03	1.01	1.00	1.00	1.01	1.03	1.11	1.32	2.00
	60	1.67	1.32	1.15	1.06	1.02	1.00	1.00	1.00	1.00	1.02	1.08	1.25	1.75
	50	1.64	1.30	1.14	1.06	1.02	1.00	1.00	1.00	1.00	1.01	1.06	1.22	1.67
	40	1.61	1.28	1.14	1.06	1.02	1.00	1.00	1.00	1.00	1.01	1.06	1.19	1.59
	30	1.61	1.28	1.14	1.06	1.02	1.00	1.00	1.00	1.00	1.01	1.08	1.20	1.61
	20	1.61	1.28	1.14	1.06	1.02	1.00	1.00	1.00	1.00	1.01	1.08	1.22	1.64

3.4 Hand-Arm Vibration Exposure Points System with Age and Climate Multipliers

When applying the HAV exposure points system (e.g., in Hong Kong), the U.K.'s original HAV exposure standards remain the same (i.e., 100 and 400 points, respectively, for the action and limit values of HAV exposure). However, the HAV exposure points for construction workers are allocated according to different age groups and climate effects. For example, for a breaker operator between 50 – 59 years of age working in a mild climate (e.g., temperature = 21°C and relative humidity = 60%), the age multiplier is 1.98, as the OR for this age group is 1.98 according to Table 7. Besides, the climate (temperature and humidity) multiplier is 1 (Table 9). Therefore, the final multiplier used is 1.98 × 1 = 1.98 for this age group in a mild climate. Based on Eqs. (1) and (3), a new HAV exposure points system for this age group in a mild climate is constructed in Table 10.

Table 10 Suggested HAV exposure points system for construction workers (50 – 59 years of age) in a mild climate

Vibration magnitude (m/s^2)											
	40										
	30	891									
	25	619	1238								
	20	396	792								
	19	357	715	1430							
	18	321	642	1283							
	17	286	572	1144							
	16	253	507	1014							
	15	223	446	891							
	14	194	388	776							
	13	167	335	669	1338						
	12	143	285	570	1140						
	11	120	240	479	958	1437					
	10	99	198	396	792	1188					
	9	80	160	321	642	962	1283				
	8	63	127	253	507	760	1014	1267			
	7	49	97	194	388	582	776	970	1164		
	6	36	71	143	285	428	570	713	855	1140	1426
	5.5	30	60	120	240	359	479	599	719	958	1198
	5	25	50	99	198	297	396	495	594	792	990
	4.5	20	40	80	160	241	321	401	481	642	802
	4	16	32	63	127	190	253	317	380	507	634
	3.5	12	24	49	97	146	194	243	291	388	485
	3	9	18	36	71	107	143	178	214	285	356
	2.5	6	12	25	50	74	99	124	149	198	248
	2	4	8	16	32	48	63	79	95	127	158
	1.5	2	4	9	18	27	36	45	53	71	89
	1	1	2	4	8	12	16	20	24	32	40
		15m	30m	1h	2h	3h	4h	5h	6h	8h	10h
		Daily Exposure Time									

If another breaker operator from the same age group works in a hot and humid climate (e.g., temperature = 32°C and relative humidity = 80%), the age multiplier is still 1.98. The climate (temperature and humidity) multiplier becomes 1.15 (= 1/0.87) according to Table 9. Therefore, the final multiplier is 1.98 × 1.15 = 2.28 for this worker in hot and humid working conditions. Using Eqs. (1) and (3), a new HAV exposure points system for this age group on hot and humid working days is shown in Table 11. Using the same principle, other age and climate conditions can be considered.

Table 11 Suggested HAV exposure points system for construction worker (50 – 59 years of age) in a hot and humid environment

Vibration magnitude (m/s^2)	15m	30m	1h	2h	3h	4h	5h	6h	8h	10h
40										
30	1026									
25	713	1425								
20	456	912								
19	412	823								
18	369	739								
17	329	659	1318							
16	292	584	1167							
15	257	513	1026							
14	223	447	894							
13	193	385	771							
12	164	328	657	1313						
11	138	276	552	1104						
10	114	228	456	912	1368					
9	92	185	369	739	1108					
8	73	146	292	584	876	1167				
7	56	112	223	447	670	894	1117	1341		
6	41	82	164	328	492	657	821	985	1313	
5.5	34	69	138	276	414	552	690	828	1104	1379
5	29	57	114	228	342	456	570	684	912	1140
4.5	23	46	92	185	277	369	462	554	739	923
4	18	36	73	146	219	292	365	438	584	730
3.5	14	28	56	112	168	223	279	335	447	559
3	10	21	41	82	123	164	205	246	328	410
2.5	7	14	29	57	86	114	143	171	228	285
2	5	9	18	36	55	73	91	109	146	182
1.5	3	5	10	21	31	41	51	62	82	103
1	1	2	5	9	14	18	23	27	36	46
	Daily Exposure Time									

In addition to this exposure points system, preventative measures are also important. In terms of equipment, vibrating tools should be equipped with dampening designs to minimize the effects of HAV on the human body (e.g., blood vessels, nerves and muscles)[55,56]. Moreover, manufacturers should ensure the normal functioning of vibrating equipment by providing regular maintenance. Furthermore, warning labels should be clearly shown on the vibrating tools if they may cause HAV injuries in construction workers. Meanwhile, construction workers should bear the responsibility of protecting themselves from HAVS. First, they should minimize the duration with which they operate vibrating tools (i.e., by turning off the devices when not in use). Second, protective gloves should be worn during long hours of HAV exposure. Third, they should limit cigarette smoking, as nicotine reduces blood supply and thus raises the probability of developing VWF. Fourth, they should seek medical advice if they feel unwell after long hours of HAV exposure. Regular body checks are also recommended for construction workers. More importantly, the real-time monitoring of construction workers' HAV exposure points using a small and portable HAV meter is also required. Whenever vibration action or limit values are reached, the meter uses sound alerts with vibration inform the construction workers that the thresholds have been exceeded.

4 Conclusions

Human vibration, including hand-arm vibration and even whole-body vibration[57], is a serious but hidden health risk among construction workers that is often overlooked. From a safety point of view, optimizing the existing regulations and standards to improve occupational safety is necessary. Therefore, we propose a quantitative guideline based on the U.K.'s HAV exposure points system that considers age and climate effects. The age multiplier of different age groups and the climate multiplier of hot and cold climates were determined by reviewing the literature. The exposure points system is indeed a quantifiable approach for protecting construction workers from HAV. Although many other uncertain factors (e.g., body strength, gender and race) may affect the degree of HVAS that develops, a measurable scale to prevent excessive exposure to vigorous vibration for general construction workers is highly desired. The simple idea presented here is only to optimize its applicability in different age groups and climates. The present data were extracted from the literature, however, *ad hoc* field-measurement studies will be conducted for specific ages, climates and other uncertain factors. Meanwhile, the outcome of this human-based study, an HAV exposure points system with age and climate factors, is suggested to be a better guideline for limiting HAV exposure and protecting construction workers from HAVS. Countries or cities where do not use HAV exposure limits are highly encouraged to establish regulations or detailed guidelines on HAV to protect their construction workers. In the meantime, the prevention of the adverse health effects of HAVS should be further promoted to contractors and construction workers to raise their awareness of this hidden danger.

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