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An Investigation of the Effects of Drill Operator Posture on Vibration Exposure and Temporary Threshold Shift of Vibrotactile Perception Threshold

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Abstract: The present study involved performing an experiment to clarify whether vibration measurement values on the tool handle, in accordance with ISO 5349-1, can assess risk from workplace environments. The study investigated the relationship between the vibration magnitude of a hand-held electric drill with different operating postures. The experiment included the determination of the participant's temporary threshold shift (TTS) of vibrotactile perception threshold (VPT) at the tip of the index finger. The experimental hypothesis was that the vibration measurement values on the tool handle, in accordance with the ISO 5349-1 standard, include the effect of posture on the vibration measurements obtained despite the variation in posture and test participants. The hand-transmitted vibration (HTV) was applied using a hand-held electric drill applied to a pre-cast concrete paving slab substrate (600 $\times$ 600 $\times$ 50 mm, 55 MPa) using a 10 mm diameter masonry drill bit (without hammer action). The tool was operated using the right hand on twelve male subjects with three working postures (n = 36). Vibration was measured in three orthogonal directions according to the international standard ISO 5349-1 procedure. Vibration magnitudes were expressed as root-mean-square (r.m.s.) acceleration, frequency-weighted using the W_h frequency weighting. Clause 4.3 states that the characterisation of the vibration exposure is assessed from the acceleration of the surface in contact with the hand as the primary quantity. The experimental results indicate that the TTS following vibration exposure is not related to the measured vibration magnitude on the tool handle. Therefore, the automatic inclusion of posture and test participant variation is not proven. The results suggest that the vibration measurement values on the tool handle do not predict the TTS after hand-transmitted vibration in varying posture across the test participants. The research concludes that tool handle vibration measurement, in accordance with ISO 5349-1, does not properly assess the potential hazard from authentic workplace tool usage conditions of varying postures.

Keywords: hand–arm vibration; posture; vibrotactile perception

1. Introduction

In industrial workplace environments, operatives are exposed to hand-transmitted vibration (HTV) with a broad range of postures, tools and tool use operations being adopted. Industrial operatives are prone to a range of conditions affecting the musculoskeletal, neurological, and vascular systems collectively known as hand–arm vibration syndrome (HAVS). Academic research has clarified the relationship of vibration dose and the human response to vibration and subsequent diseases that ensue [1–4]. These studies were undertaken in live working environments and reflected in-use conditions. The vibration is typically measured in three orthogonal planes according to the procedure established by the international standard ISO 5349-1 [5]. The vibration magnitudes were expressed as root-mean-square (r.m.s.) acceleration, which was frequency-weighted and band-limited using the W_h filter in accordance with ISO 5349-1. The root-sum-of-squares (vibration total value, a_{hv}) of the frequency-weighted acceleration values for the x, y and z axes are calculated using:

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

ISO 5349-1:2001 Clause 4.3 states that the characterisation of the vibration exposure is assessed from the acceleration of the surface in contact with the hand as the primary quantity. Therefore, the standard assumes that the hand-transmitted vibration exposure magnitude is the tool handle vibration measurement—or that obtained from manufacturers test protocols to establish declared values for adopting in industry. The method of evaluation of vibration exposure described in ISO 5349-1:2001 takes into account the frequency content, the duration of exposure in a working day and the cumulative exposure to date.

The established standards ISO 5349-1 [5], ISO 5349-2 [6] and ISO 8041-1 [7] focus upon measuring the vibration magnitude from the tool handle or on different seat locations. Furthermore, declared values are often used to undertake operator exposure assessments as the equipment, technical expertise and associated costs of conducting work environment assessments are prohibitive. ISO 5349-1:2001 provides information on the factors likely to influence the effects of human exposure to hand-transmitted vibration in industrial work environments as:

1. Direction of the vibration.
2. Working method and operator's skill.
3. Age, constitution and health of operator.
4. Coupling forces (grip and feed force).
5. Hand, arm and body posture.
6. Condition of the machinery used, accessories or work pieces used.
7. Area of the hand in contact with the tool.

ISO 5349-1 [5] and ISO 5349-2 [6] emphasise that the measurement of hand-transmitted vibration exposure for risk assessment purposes should be conducted at workplaces under real tool operating conditions. The effects of the influencing factors on tool vibration should have been automatically considered in the context of workplace assessments. In the present study, the experiment considers participant exposure and compares the tool handle vibration with TTS of VPT in an attempt to replicate authentic workplace ergonomic conditions. The experimental hypothesis is that the vibration measurement values on the tool handle, in accordance with the ISO 5349-1 standard, incorporates the effects of influencing factors on tool vibration measurement in workplaces. Despite variation in tool usage posture and test participants, the tool handle vibration measurement approach can assess the hazards associated with authentic workplace vibration exposure. Therefore, the presented study investigates the relationship between the vibration magnitude of a hand-held electric drill operated in three alternative postures whilst drilling into pre-cast concrete paving slabs. The study examines the effect of different operating postures and the temporary threshold shift (TTS) of participant vibrotactile perception threshold (VPT) at 125 Hz on the index finger.

2. Experimental Method

2.1. Test Participants

Vibration data were obtained from a sequence of controlled tests performed using typical industrial power tools in a laboratory setting. Twelve healthy male subjects aged between eighteen and twenty-four years of age with no previous history of workplace vibration exposure were selected as test participants. Alcohol, nicotine and caffeine intake were prohibited prior to and for the duration of the experiments in accordance with ISO 13091-1 [8]. The experimental regime was approved by the Edinburgh Napier University research ethics committee and all participants were willing volunteers with individual consent being obtained prior to commencing the experiments.

2.2. Experimental Method

Tool handle vibration was measured for a period of two minutes using ISO 8041 compliant reference instrumentation. The equipment included a Svantek SV106 and a Brüel & Kjær Photon+ with RT Pro Software. Svantek SV150 and Brüel & Kjær 4520-001 accelerometers were mechanically fixed to the tool handle in accordance with ISO 28927-5 [9]. Accelerometer mounting and the application of necessary frequency weightings were undertaken in compliance with ISO 5349-1.

To examine the TTS in fingertip vibratory sensation, the VPT was measured before and after participants were exposed to HTV, as shown in Figure 1. The room temperature was maintained at 22 °C. Vibration was applied to the right hand through the grip handle of the selected power tool. The participants were instructed to clasp the handle tightly and consistently with part of the palm and fingers with an appropriate grip force in the posture being considered. The elapsed exposure time was two minutes. The threshold of 125 Hz vibratory sensation was measured at the index finger of the right hand. It is important to consider the specific frequency being tested as variation in this may provide different results. VPTs were then determined using a vibrotactile sensation meter (RION type AU-02A). VPT was determined using the method of adjustment. In this method, the measurement was performed three times. VPT was calculated as the mean value of three measurements obtained less than 30 s after the end of the power tool use exposure. TTS was defined as the difference (in decibels, dB) of the VPT before and after the vibration exposure. The experiment was performed on three different days. To study the TTS in fingertip vibratory sensation, the VPT was measured before and after subjects were exposed to HTV.

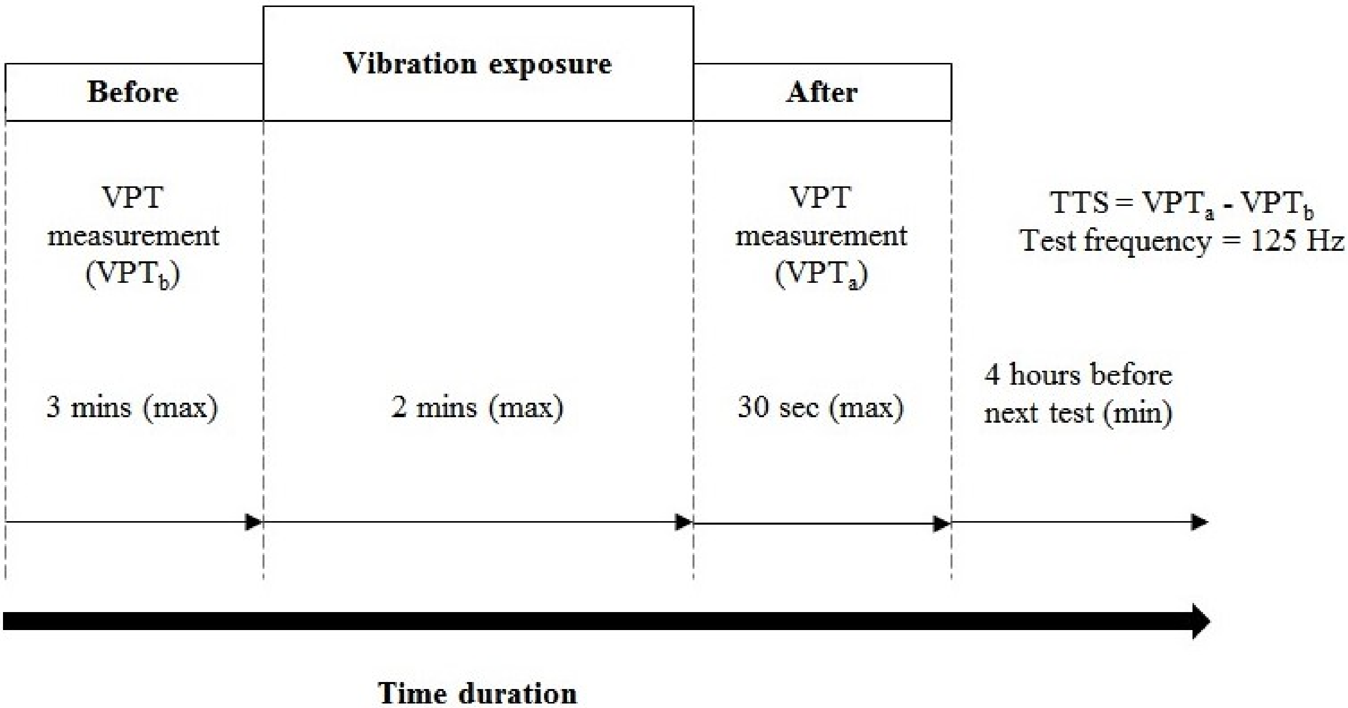

Figure 1. Experimental procedure for VPT measurement before and after tool vibration exposure.

TTS results were manually recorded at the test bench in close proximity to the experimental working area. Tool handle data were recorded using the Svantek SV106 device and the Photon+ software interface connected to a laptop computer. Post-processing of acquired data was undertaken with Matlab 2019a and Python programming.

The TTS was calculated using the following equation:

$$TTS(f) = VPT_A - VPT_B(\mathrm{dB}) \tag{2}$$

where $TTS(f)$ (dB) is the test frequency (f) of the temporary threshold shift of vibrotactile perception threshold, VPT_A (dB) is the vibrotactile perception threshold after the power tool use vibration exposure, and VPT_B (dB) is the vibrotactile perception threshold before the power tool use vibration exposure.

Three typical operating postures were considered to reflect working practice, as shown in Figure 2. These included:

- Vertical downwards (single handed) similar to ISO 28927-5 test protocol.
- Horizontal (tool located in front of subject, held with both hands).
- Vertically upwards (tool located overhead, single handed use).

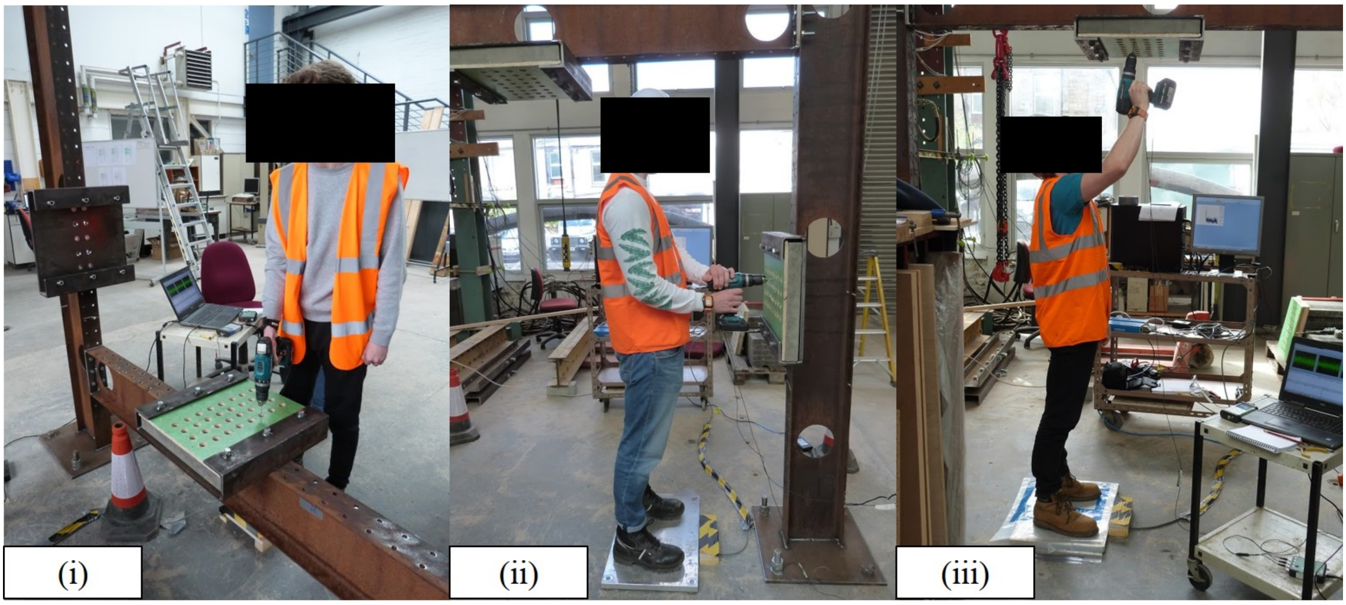

Figure 2. Test postures (**i**) vertical downwards similar to ISO 28527-5 posture, (**ii**) horizontal and (**iii**) vertical overhead.

All participants performed individual tests assuming each of the nine tool and posture configurations. The participants used a Makita 18V lithium-ion battery powered hand-held drill.

3. Results

Table 1 shows a summary of the results for the three postures tested using twelve test participants (n = 36). Tool handle vibration measurements and TTS results are presented. Tables 2 and 3 show means, standard deviations and standard errors for the test results.

Figures 3 and 4 visually present the results as box plots showing the median and quartiles of the tool vibration and TTS results. Minimum, lower quartile, median, upper quartile and maximum values are shown. Figure 3 identified that test participant F conducting the Posture 1 test was a potential outlier. However, the test results were not removed from the analysis.

Table 1. Test results summary (all participants).

Participant	Posture 1		Posture 2		Posture 3	
	Tool Vibration (ms^{-2})	TTS (dB)	Tool Vibration (ms^{-2})	TTS (dB)	Tool Vibration (ms^{-2})	TTS (dB)
A	5.3	20.00	3.7	15.00	3.7	22.50
B	5.5	22.50	3.1	15.00	3.1	25.00
C	5.3	25.00	2.0	17.50	2.0	20.00
D	5.2	22.50	4.5	20.00	4.5	17.50
E	5.7	20.00	4.4	20.00	4.4	25.00
F	4.9	20.00	3.6	20.00	3.6	27.50
G	5.5	17.50	3.0	12.50	3.0	20.00
H	5.1	17.50	3.6	15.00	3.6	20.00
I	5.3	20.80	4.0	20.00	4.0	20.00
J	5.5	22.50	2.8	22.50	2.8	25.00
K	5.4	21.70	3.7	15.00	3.7	22.50
L	5.3	15.00	2.8	17.50	2.8	17.50

Table 2. Tool handle vibration (ms^{-2}) test results statistics.

Posture	*n*	Mean (ms^{-2})	S.D	C.V	S.E	95% Conf.	Interval
Posture 1	12	5.33	0.21	3.94	0.06	5.19	5.46
Posture 2	12	3.94	0.31	8.05	0.09	3.73	4.14
Posture 3	12	3.43	0.72	21.05	0.20	2.97	3.89

Table 3. TTS (125 Hz) test results statistics.

Posture	*n*	Mean (dB)	S.D	C.V	S.E	95% Conf.	Interval
Posture 1	12	20.41	2.74	13.42	0.79	18.67	22.15
Posture 2	12	17.50	3.01	17.22	0.87	15.58	19.41
Posture 3	12	21.87	3.22	14.72	0.92	19.82	23.92

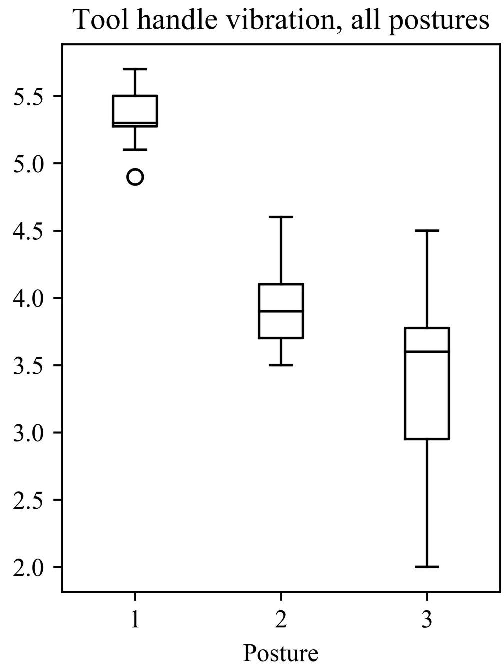

Figure 3. Tool handle vibration magnitude (ms^{-2}) for all postures.

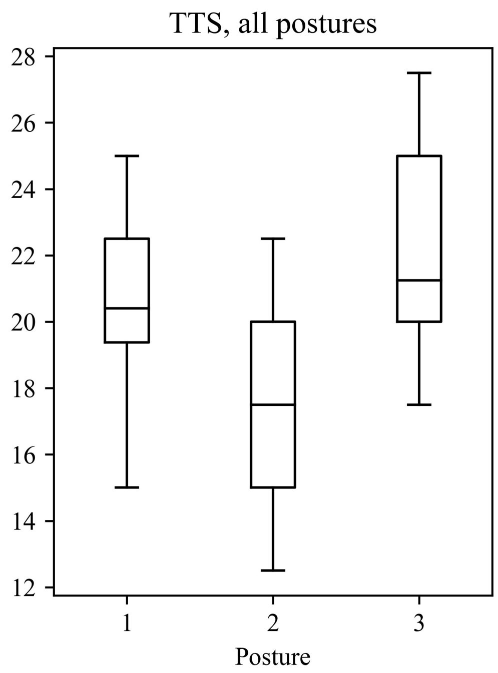

Figure 4. TTS (125 Hz) on the tool handle for all postures.

4. Statistical Analysis of Results

The data were tested from normality and homogeneity. A Shapiro–Wilk test was used to determine if the data (tool vibration and TTS measurements) could have been produced from a Gaussian distribution. The results of the Sharpiro–Wilk tests were significant (>0.05, 5%) and were calculated as W = 0.946, $p = 0.079$ and W = 0.957, $p = 0.178$ for tool handle vibration and TTS results, respectively. Homogeneity was tested using a Levene test for equality of variance. The Levene test used an F-test to test the null hypothesis that the variance is equal across the three posture groups. The tool vibration and TTS results had p-values of 0.0078 (<0.05) and 0.6325 (>0.05), respectively. The tool vibration results demonstrate a violation of the assumption of homogeneity of variances and indicate that heteroskedasticity exists. Therefore, a Welch-ANOVA test was applied to test for variances in the mean values of the tool vibration results for different postures.

Tests ($n = 36$) were conducted to examine the relationship between TTS and the vibration magnitude on the tool handle when using an impact drill with different ergonomic postures. The average tool vibration measurement was 4.23 ms^{-2} 95% CI (3.92,4.55) with posture group means of 5.33 ms^{-2} 95% CI (5.19,5.46) for Posture 1, 3.94 ms^{-2} 95% CI (3.73,4.14) for Posture 2 and 3.43 ms^{-2} 95% CI (2.97,3.89) for Posture 3. There was a statistically significant difference between the postures and their effect upon the tool vibration measurement as determined by a one-way ANOVA, ($F(2,34) = 52.18$, $p = 0$). The effect of posture upon the tool handle vibration measurement was statistically significant ($p < 0.05$).

The mean TTS (125 Hz) measurement was 19.93 dB 95% CI (18.76,21.09) with posture group averages of 20.41 dB 95 % CI (18.67,22.15) for Posture 1, 17.50 dB 95 % CI (15.58,19.41) for Posture 2 and 21.87 dB 95 % CI (19.82,23.92) for Posture 3. There is a statistically significant difference between the postures and their effect upon the TTS measurement as determined by a one-way ANOVA, ($F(2,34) = 6.62$, $p = 0.0038$). The effect of posture upon the TTS (125 Hz) results was statistically significant ($p < 0.05$).

Post-hoc (a posteriori) tests were applied to determine the specific postures that generated differences in means between the groups. A Tukey HSD test was applied to the data set. Tables 4 and 5 shows the results of the tests for the tool vibration and TTS (125 Hz) results. Tables 4 and 5 present the results of the Tukey HSD tests. There were statistically significant differences between the means of the posture groups for the tool vibration measurements. Furthermore, the results for the TTS (125 Hz) results were statistically significant when considering the results for Postures 2 and 3 (p-value = 0.0031 < 0.05).

Table 4. Multiple comparison of tool vibration means (Tukey HSD, FWER = 0.05).

Group 1	Group 2	Mean Diff. (ms^{-2})	p-Value	Lower	Upper	Reject
Posture 1	Posture 2	−1.391	0.001	−1.864	−0.919	True
Posture 1	Posture 3	−1.900	0.001	−2.372	−1.427	True
Posture 2	Posture 3	−0.508	0.032	−0.980	−0.035	True

Table 5. Multiple comparison of TTS (125 Hz) means (Tukey HSD, FWER = 0.05).

Group 1	Group 2	Mean Diff. (dB)	p-Value	Lower	Upper	Reject
Posture 1	Posture 2	−2.916	0.058	−5.920	0.086	False
Posture 1	Posture 3	1.458	0.468	−1.545	4.461	False
Posture 2	Posture 3	4.375	0.003	1.371	7.378	True

5. Discussion of Results

Table 1 shows variation in the TTS value for each participant; however, the vibration magnitude remains relatively constant. Previous experimental results [10] have identified a significant linear correlation between vibration magnitude and TTS. The experimental results show the TTS value increasing and an associated increase in HTV. However, the measured power tool vibration magnitude shows a low standard deviation across all participants and postures with statistically significant results and variance in the means across all postures. The test data also show that there are statistically significant results for the test of variance when comparing mean TTS (125 Hz) Postures 2 and 3 and Postures 1 and 3. It is important to note that if the tool had no 125 Hz component, then the test results would potentially vary.

The results obtained for the tool handle vibration measurement are similar for each posture; however, the TTS results for each test participant differs, suggesting that the factors outlined in Annex D of ISO 5349-1 contribute to the vibration transmitted to the hand–arm system. Existing protocols consider the tool handle vibration values as already including such factors. The results presented demonstrate that there is variation in the individual response to this vibration source and that the evaluation method outlined in ISO 5349-1 has a physiological effect upon the test participants and has implications on the accurate assessment of exposure risk. The conclusions of the present study cannot be extended to the general case without further testing of tools with different vibration spectra and gripping conditions. If the tool handle vibration values remain relatively similar, the TTS results for each participant are showing statistically significant variance, indicating that the factors considered in Annex D of ISO 5349-1 are associated with vibration transmitted to the wrist. It is considered that when the vibration from the handle is transmitted to the wrist, the vibration value transmitted to the wrist is changed due to the influence on the Annex D factors and the test participants' individual approach. The experimental results show that in certain postures the HTV transmission may increase. Therefore, the tool vibration measurement values on the tool handle are potentially unsuitable for risk assessment purposes.

Previous research [11–15] examined how the vibration from the handle is transmitted to each part of the subject's arm when varying the posture and grip force. Experimental results clarified that the vibration from the handle can vary. However, the relationship between the variation of the transmitted vibration and physiological effect has not been discussed. Radziukevich [16] suggested that the TTS in VPT at the end of the working day should be collated and recorded alongside the permanent threshold shifts (PTS) that develop over longer time periods. Malinskaya [17] discovered that the mean TTS of operatives, after a day of work that included vibration exposure, corresponded to the PTS of vibratory sensation that occurred in that group after ten years of exposure. This may suggest that the TTS after daily vibration exposure might be used to indicate PTS after prolonged exposure. Clemm [18] showed that the PTS measurement using VPT as an index is effective as an early diagnosis of the effect of wrist vibration disorder on the nervous system.

Considering the transmission of vibration from a tool grip handle, the transmission to the hand-arm system changes due to the influence of the factors identified in Annex D during industrial use of hand-held tools in the workplace. The result alludes to the use of tool handle measurement values being applied to hand–arm vibration assessment in accordance with ISO 5349-1 and ISO 5349-2 is not accurately assessing risk in industrial workplace settings. The results show that despite the power tool vibration magnitude remaining relatively constant, the participant TTS value is variable. The observations infer that the HTV exposure magnitude is increasing when transmitted to the wrist. Therefore, the tool handle vibration value adopted in accordance with ISO 5349 is subsequently not suitable for assessing human operative exposure to vibration hazards of this nature. This result has a potential impact on the risk assessment process adopted for such working environments.

Hartung [19] examined the acute response of the hand–arm system varying vibration conditions. The vibration value at the tool handle was measured for each subject, and the average value of the measured values was considered as a representative value of their vibration exposure value. The gripping force of the tool handle was then changed. The TTS of VPT was measured, and it was shown that the TTS value changes depending on the gripping force.

From the results, the TTS value also increased as the gripping force increased, but when considering the average value of the vibration value and the effect on the human body due to the use of a vibrating tool, it has been shown that it is necessary to measure the gripping force. The results obtained indicated that the vibration value is constant and the change in gripping force affects the TTS value because the vibration value transmitted from the handle to the wrist increases due to the change in gripping force. It is considered that the TTS value is increasing. Therefore, the idea that the handle vibration value measurement method automatically considers the influencing factors of Annex D to measure the vibration value remains questionable.

Lofgren [20] experimented with variations to grip force and assessment of TTS of VPT. The results demonstrated that as the grip force increased, the tool vibration value decreased and the TTS value increased. These results emphasised the importance of evaluating grip force; however, the TTS value was conversely large even though the vibration from the tool handle was low. The results demonstrated that the TTS value was increasing due to the vibration transmission to the wrist increasing as the gripping force increased. It appears that the physiological effect on the human body is not captured by measuring the vibration value on the tool handle.

The effectiveness of vibration-reducing (VR) gloves is conventionally assessed based on the vibration transmissibility of the gloves [21]. This study proposed a method for analysing and assessing the effectiveness of VR gloves based on how gloves affect the vibration power absorption (VPA) of the hand–arm system and its distribution. In addition to the individual differences, the actual effectiveness of the gloves at workplaces may also vary in conjunction with other influencing factors such as: the vibration direction, applied hand forces, hand–arm posture, vibration magnitude, tool handle shape, tool handle covering materials, glove conditions (worn condition and duration of use), and environmental conditions (temperature, moisture). It would be impossible to consider all these factors in a single study. The research only simulated the averaged responses of the subjects wearing new gloves to the vibration excitation along the forearm direction or z-direction under the same subject postures and hand forces as those required in the standard glove test. Since the specific values of the distributed VPAs and the VPA-based glove vibration transmissibility spectra may vary with many of the influencing factors, the glove effectiveness may be different from that at workplaces.

From Figure 3, the vibration measurement values are changing with postures. Furthermore, the TTS values, as shown in Figure 4, are changing with postures and vibration magnitude. Considering previous TTS research, the TTS values are increasing when the vibration measurement values are increasing. However, from Figure 4, the vibration measurement values on the tool handle are changing with postures, and the TTS values are not consistent with the measurement vibration values. Specifically, although the vibration magnitude of Posture 3 is larger than other postures (1 and 2), the TTS values are not consistent with the tool handle vibration magnitude. The TTS median value is almost the same value of Posture 1.

In the present study, in all postures the vibration magnitudes are almost constant, the TTS value of individual participants vary. Even if the measured vibration value at the handle is almost the same for each subject, the TTS value may be larger or smaller for the participant.

It is considered that this difference is due to the transmission of vibration to the arm system. Therefore, it is considered that the vibration value measurement method using the handle vibration as stated in ISO 5349-1 does not incorporate the physiological effects. In addition, the effect on the individual cannot be estimated by the vibration measurement method (ISO 5349-1) alone. The vibration value of the tool handle in combination with the effect of vibration exposure to the individual was considered. Future research should consider a standard of measuring vibration transmitted to the wrist. Such a standard should consider the potential for measurement of vibration transmission during actual working conditions and without interrupting the operative. Innovate measurement instruments should be considered in parallel with the development of revised technical standards.

Presently, many countries employ standards that use the tool vibration values in relation to preventing HAVS. The tool vibration values are not applicable to all possible postures, operatives and variation in working conditions. The results presented contribute to the evidence that suggests that the tool vibration measurement method, according to the ISO 5349-1 and ISO 5349-2, cannot capture the hand-transmitted vibration including the many affecting factors to evaluate the exposure vibration. A new evaluation method in combination with relevant equipment is required to develop innovative tools for preventing HAVS.

From these experimental results, although many countries are using the tool vibration measurement according to ISO 5349-2 for the purpose of preventing HAVS, it is clear that the values from the ISO 5349-2 are not appropriate for all factors in the real work conditions. Furthermore, from the results of Table 1, the ISO 5349-1 vibration measurement on the tool handle has limitations. From the relationship between the TTS and the vibration magnitude on the tool handle for each participant, the TTS value of the vertical downward posture (Posture 1) is greater than the horizontal posture (Posture 2). However, the tool vibration magnitude was smaller than the vertical downward posture.

On the vertical upward posture (Posture 3), although the TTS value of the vertical upward posture is greater than the vertical downward posture, the tool vibration magnitude was less than the vertical downward posture. Therefore, this infers that the vibration value from the ISO 5349-1 standard should not be applied to the different posture and subjects. Building upon previous research and from the limited experimental results presented, although many countries use the tool vibration measurement values according to the ISO 5349-1 and -2 standards for preventing HAVS, it is evident that the measured vibration magnitudes on the tool handle may not be applicable to all the postures and operative variability relating to authentic work conditions.

Despite international adoption of the declared tool vibration values, from these limited experimental results, it is clear that the values from the tool test protocol or the measured vibration magnitudes are not applicable to all postures and participants. The experimental results demonstrate that variation in actual working methods and operative stance has an impact upon the tool handle vibration values and TTS of VPT.

6. Conclusions

Internationally, standards are adhering to the use of tool vibration values based upon ISO 5349-1 to prevent HAVS among the industrial workforce. It is unclear whether the values from the proposed test protocols or the measurement of vibration magnitudes (in accordance with ISO 5349-1) are applicable to all scenarios in authentic working conditions.

The experimental method was developed to clarify whether tool vibration measurement values can be used to assess the risk of authentic workplace vibration exposure. The conclusions of the present study are somewhat limited by the presence of a single tool and should be confirmed with future studies considering other tools and usage conditions.

The following conclusions were drawn:

(a) The existing international standards for assessing human exposure to hand–arm vibration based upon the ISO 5349-1 utilising tool vibration measurement values may not effectively capture posture factors and individual human response to vibration.
(b) A new evaluation method to assess HTV inclusive of the limitations outlined within Annex D would be desirable.
(c) The results demonstrate that there is a potential requirement for apparatus suitable for hand-transmitted measurement on the human operative as a means of assessing real time work environment exposure.

These results indicate that there is scope for development of a suite of new evaluation methods or potential for innovative equipment, which may provide a more realistic and practical assessment of HTV exposure. It would be myopic to not consider HAVS prevention without improvements to the incorporation of dose adjustments reflecting actual working conditions. Capturing the factors outlined in ISO 5349-1 Annex D has presented a significant challenge in assessing HTV exposure and HAVS assessment in work-face settings. Future research should consider further experiments to examine the effect of posture on the physiological effects of vibration exposure. Strict adherence to the ISO 5349-1 standard and the use of declared vibration values may be contributing to erroneous dose evaluation and inferior operative health and safety management practices for operatives using vibrating hand-held power tools. In relation to operative work-face measurements, the practicality and technical requirements for implementation of the assessment protocol often precludes it from being performed at all.

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Informed Consent Statement: Informed consent was obtained from all experimental participants involved in the study.

Data Availability Statement: The experimental data set is available upon request.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

HAV	Hand–arm vibration
HTV	Hand-transmitted vibration
MEMS	Micro-electromechanical systems
TTS	Tactile threshold shift
VPA	Vibration power adsorption
VPT	Vibrotactile perception threshold
VR	Vibration reducing

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