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Determination of hand-transmitted vibration risk on the human

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ABSTRACT

Objective: The purpose of this paper is to examine the effectiveness of the proposed consideration for hand-transmitted vibration measurement on the human.
Method: To obtain the temporary threshold shift (TTS) in the fingertip vibrotactile perception threshold, the vibrotactile perception thresholds were measured before and after the subjects were exposed to hand-transmitted vibration from the hand-held tool. The vibration magnitude has been measured by using conventional vibration measurement on the tool and by using the proposed consideration vibration on the human simultaneously.
Results: The proposed hand-transmitted vibration measurement on the subject was proportional with increasing TTS. In contrast the data from conventional vibration measurement on the tool shows a relatively constant vibration level while TTS increases within a subject group.
Conclusion: The proposed measurement method of hand-transmitted vibration on the subject captures at least some of the effects of factors relating to the human interaction with the tool identified within Annex D of the ISO 5349-1 standard. The effectiveness of the proposed hand-transmitted vibration measurement consideration on the human for improved understanding of tool vibration exposure has been shown.

1. Introduction

Hand-arm vibration syndrome (HAVS) is a recognised industrial disease induced by excessive exposure to vibration through occupational tasks involving vibrating machinery. HAVS comprises a range of disorders affecting the peripheral circulatory system, peripheral nervous system and muscular skeletal system of the hand and arm. As a progressive and irreversible condition, the ability to predict a rate of progression and take timely preventative action through exposure reduction or complete elimination of hazardous exposure is highly desirable. The established method for assessing exposure has been standardised in the form of ISO 5349 (BSI, 2001a) with employers being required to control exposure levels to predetermined limits within their respective territorial legislation. Despite the existence of international standards concerning exposure assessment and regional legislation regarding working practices, reported cases of HAVS remain significant as indicated by disability benefit claims in the UK (HSE, 2005). Since the condition typically takes many years to become symptomatic there is significant variation in the reported rate of progression relative to exposure.

The CEN technical report CEN/TR 15350 (BSI, 2013) identifies the difficulties in capturing all the factors affecting the vibration level of a tool and recognises the expense in doing so. CEN/TR 15350 advises that the exposure to vibration does not only depend on the machine used but also to a large extent on the quality of inserted tools, the work situation and operator behaviour. It concludes that these factors must be considered to make an ideal assessment of vibration exposure. Clause 4.3 of ISO 5349-1 states that although characterisation of the vibration exposure currently uses the acceleration of the surface in contact with the hand as the primary quantity, it is reasonable to assume that the biological effects depend to a large extent on the coupling of the hand to the vibration source. Also, that it should also be noted that the coupling can affect considerably the vibration magnitudes measured. Finally, that the vibration measurements shall be made with forces which are representative of the coupling of the hand to the vibrating power tool, handle or workpiece in typical operation of the tool or process.

In the work site, the acceleration magnitude on the tool handle has been considered as a hand-transmitted vibration magnitude, as it is following the approach of ISO5349-1. However, Annex D of ISO 5349-1 identifies that the hand-transmitted vibration in working conditions may also be affected by many factors. A more ideal assessment of the effect of exposure to vibration in working conditions would measure

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hand-transmitted vibration accounting for factors affecting the tool handle vibration measurement.

Some of the affecting factors have been investigated by researchers. For example, the effect of hand coupling action on vibration transmission through to the hand arm system has been explored in historical studies. Maeda et al. (2007) investigated the effect of hand coupling actions on the TTS of vibrotactile perception, illustrating that hand coupling actions affect the human response. Maeda and Shibata (2008) also provided evidence of the effect of operative posture on TTS results. Also, the transmission factor of coupling force was examined by Pan et al. (2018) and Kaulbars (1996) in laboratory conditions. Pan et al. (2018) established that the coupling action influenced the vibration transmission to the wrist from the tool handle emitted vibration but did not model this as a coupling weighting coefficient. From these results, although it is clear that the vibration transmission is changed by the posture, coupling force, direction, handle diameter, and so on, the research does not show how to take such affecting factors into the vibration magnitude from the tool handle to the human hand, to determine the hand-transmitted vibration magnitude. The effect of an individual factor on vibration magnitude has only been studied experimentally in isolation. It could be concluded from this previous research that an evaluation method on the human is needed to evaluate the hand-transmitted vibration magnitude.

A direct assessment of exposure to hand-transmitted vibration in working conditions could enable a more compelling assessment of the relationship between exposure and the epidemiological data of previous studies. The researchers would also propose that a more direct assessment of exposure risk is essential to enable more effective preventative measures to be implemented.

The research presented examines two principals. The first is the proposal of the hand-transmitted vibration measurement on the human for addressing the factors identified in annex D of ISO 5349-1. The second is the demonstration of the effectiveness of the proposed methodology for assessing the human response to exposure to hand-transmitted vibration.

2. Proposed consideration of hand-transmitted vibration on the human

Annex D of ISO 5349-1 identifies several factors that impact the hand-transmitted vibration magnitude. The proposed consideration of this study, to account for affecting factors on the vibration magnitude from the tool handle, is to measure on the human, to determine hand-transmitted vibration magnitude. Equations (1)–(3) are provided to illustrate the capture of individual affecting factors of Annex D of the ISO 5349-1 standard and their cumulative effect on the resultant tool handle vibration magnitude “a_v” when transmitted through to the human subject “a_{hv}” in the three orthogonal axes.

$$a_{hx}(t) = a_x(t) H_{FW} Ha_x Hb_x Hc_x Hd_x He_x Hf_x Hg_x Hh_x Hi_x Hj_x Hk_x Hl_x \tag{1}$$

$$a_{hy}(t) = a_y(t) H_{FW} Ha_y Hb_y Hc_y Hd_y He_y Hf_y Hg_y Hh_y Hi_y Hj_y Hk_y Hl_y \tag{2}$$

$$a_{hz}(t) = a_z(t) H_{FW} Ha_z Hb_z Hc_z Hd_z He_z Hf_z Hg_z Hh_z Hi_z Hj_z Hk_z Hl_z \tag{3}$$

where a_v = tool emitted vibration, a_{hv} = hand-transmitted vibration, H_{FW} = ISO 5349-1 frequency weighting and $H_{a,b,c,\ldots l}$ = weighting factors identified within ISO 5349 Annex D.

If the individual factors, or some combination of factors, from Annex D of ISO 5349 are not modelled, then a properly conducted measurement of the emitted vibration from the tool handle will carry remaining uncertainties as to the vibration magnitude transmitted to the hand. In moving the measurement point to the recipient of the vibration it is believed that the effects of at least some of the factors influencing the transformation from tool handle vibration magnitude “a_v” to the human subject “a_{hv}” can be considered. The research now examines how a wearable device can develop an “a_{hv}” value.

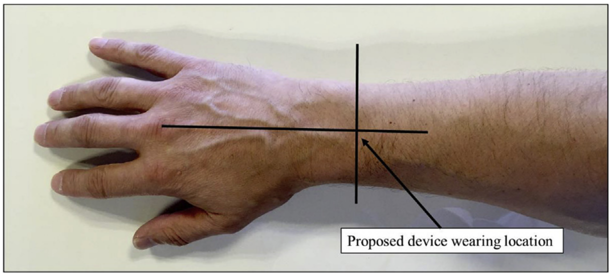

Fig. 1. Proposed device location on human arm.

The adoption of wearable technologies has become prominent in many applications and industries because of the rapid development of sensor technologies in the last decade. Awolusi et al. (2018) reviewed the use of wearable technology within the construction sector, a sector recognised as exposing individuals to high levels of risk due to the high frequency of work-related injuries and fatalities. The review concludes that a wide variety of wearable technologies are being used in other industries to enhance safety and productivity while few are used in construction.

The wearable device utilised for this study (HVW-001, Reactec Ltd.) is mounted to the subject's wrist by way of an adjustable nylon webbing strap, adjusted and fastened by way of velcro loop arrangement. The velcro arrangement allows control over the fit of the device to the user's wrist. Fig. 1 illustrates the position of the device on a subject's hand arm while Fig. 2 illustrates how the device is attached to the human subject. The orientation on the device to the subject's wrist is controlled by aligning the flat face of the device on the wearer's wrist in order that they can see the device display. This mounting method ensures that an accelerometer mounted within the device can be aligned with the direction of propagation of the vibration into the hand.

The three-axis accelerometer utilised in the device is a MEMS device from ST Microelectronics type number LIS3DSH, set at ± 8 g for measurements with an embedded self-test and an extended temperature range from −40 °C to +85 °C.

The device first captures the vibration on the wrist utilising the accelerometer. The accelerometer employs a sampling frequency of 1.6 KHz to capture a frequency range from 0 to 800 Hz. Acceleration data from each axis is captured and processed sequentially by converting from time domain to frequency domain through a 1024 point Fourier analysis incorporating a Hanning window function. The 1024 samples required for the Fourier analysis are obtained by sampling at 1.6 KHz for a duration of 0.64 s. Processing of a given frame of sampled data (n) is performed as the next frame of samples (n + 1) is being acquired. Processing of the sampled data takes 1.5 s and therefore there is a period 0.86 s when the device is not sampling.

The 1024-point FFT provides 512 power spectrum coefficients in the frequency range 0–800 Hz however only data from 0 to 650 Hz is processed which corresponds to the first 417 of the 512 coefficients. In equations (4)-(6), ‘i’ represents the frequency coefficient index and takes values between 0 and 416. In equations (4)–(6), ‘n’ represents the frame index which increases in relation to the total duration of recorded vibration trigger time divided by the combined sampling and processing time (n = t/1.5) seconds.

The sum of the frequency weighted FFT magnitude values for each axis $a_{rhx}(n)$, $a_{rhy}(n)$ and $a_{rhz}(n)$ are calculated using equations (4)–(6) respectively for each frame (n)

$$a_{rhx}(n) = \sqrt{\sum_i w_{rhx}(i)^2 .\ a_{hx}(n, i)^2} \tag{4}$$

$$a_{rhy}(n) = \sqrt{\sum_i w_{rhy}(i)^2 .\ a_{hy}(n, i)^2} \tag{5}$$

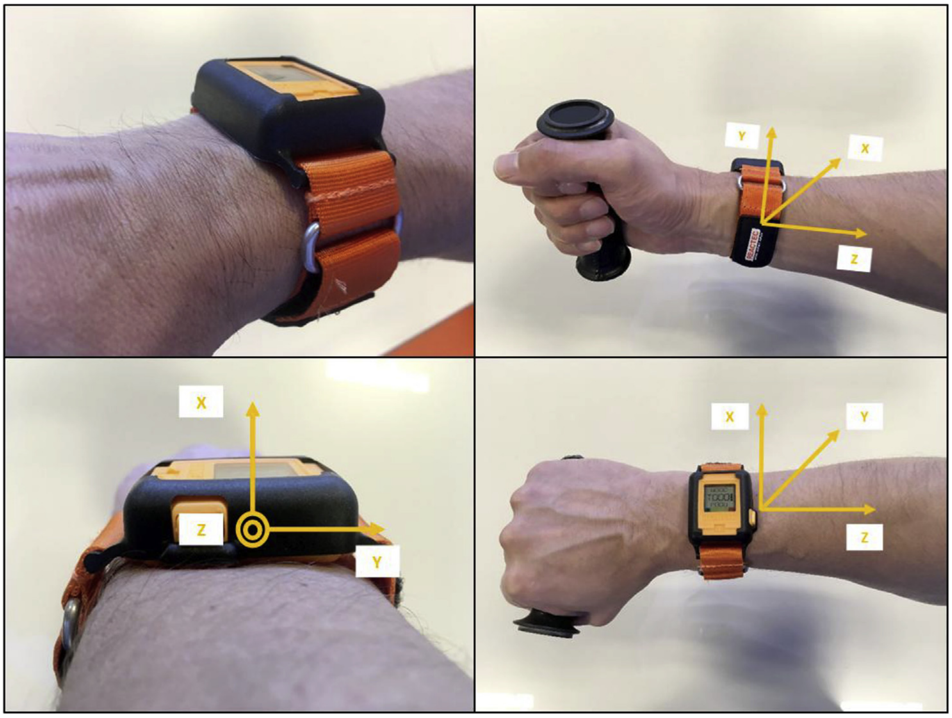

Fig. 2. HAVWEAR wrist mounting location and measurement axes.

$$a_{rhz}(n) = \sqrt{\sum_i w_{rhz}(i)^2 . \, a_{hz}(n, i)^2} \tag{6}$$

Where, $w_{rhx}(i)$, $w_{rhy}(i)$ and $w_{rhz}(i)$ are the frequency weighted transfer functions defined in equations (7)–(9). The idealized transfer functions $w_{rhx}(i)$, $w_{rhy}(i)$ and $w_{rhz}(i)$ for the specific coefficient index ‘i’ are derived by combining the transmissibility at a given frequency $fxt_x(i)$ with the corresponding ISO 5349-1 weighting ($fw_x(i)$).

$$w_{rhx}(i) = (fw_x(i)) \,/\, (fxt_x(i)) \tag{7}$$

$$w_{rhy}(i) = (fw_y(i)) \,/\, (fxt_y(i)) \tag{8}$$

$$w_{rhz}(i) = (fw_z(i)) \,/\, (fxt_z(i)) \tag{9}$$

The transmissibility at a given frequency in each axis $fxt_x(i)$, $fxt_y(i)$ and $fxt_z(i)$, between the tool user interface and the accelerometer within the wearable sensor was determined by the device manufacturer by assessing the transmission of input vibration energy across a defined frequency spectrum in the three orthogonal axes. A random broadband exposure (10–500 Hz) was simultaneously generated in three orthogonal axes (fore-aft; lateral; and vertical) by a 3D shaker system (MB Dynamics). Vibration amplitude was maintained throughout the duration of the characterisation process at 2 g in each orthogonal axis by means of a closed loop control system.

The vibration was delivered to the human hand through an instrumented handle coupled with each shaker using a flexible linkage system. The control system utilised vibration data from the instrumented handle to ensure correct vibration magnitude was maintain in each axis throughout the test cycle. The instrumented handle was equipped with a tri-axial accelerometer (Endevco, 65–100) and a pair of force sensors (Interface, SML-50) for measuring the acceleration at the user interface and applied grip force. A force plate (Kistler, 9286AA) was used to measure the push force applied to the handle. The applied and target grip and push forces were displayed on two virtual dial gauges on a computer monitor in front of the subject. The subjects were instructed to control the grip force and push force to 30N and 50N respectively. An additional accelerometer (Endevco, M35A) was attached to the subjects' skin using I.V. needle adhesive tape adjacent to the wearable sensor to provide additional reference data.

Applying the protocol described above a series of six characterisations were conducted on each test subject. Each characterisation was conducted continuously for a duration of 1 min. For the purposes of this initial characterisation subjects were limited to three. Normative data from the above series of characterisation was used to derive a mean transmissibility for each axis. Transmissibility for each specific coefficient index ‘i’ in each axis $fxt_x(i)$, $fxt_y(i)$ and $fxt_z(i)$ was derived by comparing the incident vibration magnitude measured at the shaker handle a_{sx}, a_{sy}, and a_{sz} with vibration a_{hx}, a_{hy}, and a_{hz} measured by the wearable device as characterised in equations (10)–(12).

$$fxt_x(i) = \frac{a_{hx}}{a_{sx}} \tag{10}$$

$$fxt_y(i) = \frac{a_{hy}}{a_{sy}} \tag{11}$$

$$fxt_z(i) = \frac{a_{hz}}{a_{sz}} \tag{12}$$

Transmissibility was seen to reach an effective minimum in all axes below 500 Hz therefore characterisation beyond this frequency was not deemed necessary.

A running average (r.m.s.) is determined for each of the three axes; a_{rhx}, a_{rhy} and a_{rhz} independently after frame n using equations (13)–(15) respectively.

$$a_{rhx} = \sqrt{\frac{\sum_n a_{rhx}(n)^2}{n}} \tag{13}$$

$$a_{rhy} = \sqrt{\frac{\sum_n a_{rhy}(n)^2}{n}} \tag{14}$$

$$a_{rhz} = \sqrt{\frac{\sum_n a_{rhz}(n)^2}{n}} \tag{15}$$

The running averages (r.m.s.) for each of the three axis are then combined using equation (16) to determine the overall vibration magnitude over the duration terminated by (n).

$$a_{rhv} = \sqrt{a_{rhx}^2 + a_{rhy}^2 + a_{rhz}^2} \quad (16)$$

Therefore, the derived equation (16) is proposed to represent the hand-transmitted vibration on the human with the intent to address the problems inherent in on-tool vibration measurement as described in Annex D of the ISO 5349-1 standard.

3. Experiment

The following experiments have been performed for validating the effectiveness of the proposed equation (16).

3.1. Test subjects

Tool vibration data was obtained from a series of controlled tests performed using standard industrial power tools in a laboratory setting. Male subjects (n = 12) between 18 and 24 years of age (mean = 21.8 years and S.D. 0.8 years) with no previous history of vibration exposure volunteered as subjects. An age restriction was applied to minimize the effects of age on vibrotactile sensitivity (Venkatesan et al., 2015). Alcohol, nicotine and caffeine intake were prohibited prior to and for the duration of the test protocol in accordance with ISO 13091-1 (BSI, 2001b).

No gloves were worn by the test subjects. Test subjects wore steel toe-capped laced ankle safety boots with a rubber outsole. The safety boots complied with BS EN ISO 20345:2011 (BSI, 2011). A further study investigating the impact of anti-vibration gloves on the relationships examined in this paper would be desirable.

Screening was undertaken to ensure that all participants were clear of medical conditions and occupational history that would have an impact upon the test results. The experiment was approved by the Edinburgh Napier University research ethics committee, all subjects were willing volunteers and individual consent was obtained prior to commencing the experiments.

3.2. Assessment of vibrotactile temporary threshold shift

Vibrotactile sensitivity was assessed 3 min prior to commencing the tool activity test and again within 30 s of completion of the test. The threshold of 125 Hz vibratory sensation was measured at the tip of the index finger of the right hand. A vertical force was maintained by mounting the vibration exciter on digital scales. The subjects were asked to maintain a force of 2 N by monitoring the value on a digital display. Vibration thresholds were determined using a RION type AU-02A vibrotactile sensation meter by means of gradually adjusting the vibration source noting the level at which it becomes perceptible by the subject. Thresholds were calculated by the mean values of three measurements obtained over a period not exceeding 30 s. The temporary threshold shift (TTS) test apparatus is shown in Fig. 3.

The TTS was defined as the difference (dB) of the vibrotactile thresholds before and after vibration exposure (Yonekawa et al., 1998; Maeda and Griffin, 1993). Subjects were limited to two vibration test sessions per day with a minimum of 4 h rest between each test.

Fig. 3. TTS assessment using vibratory sensation meter (Rion Company Ltd. Model AU-02A) and skin temperature measurement apparatus using thermocouple sensor (RS 206–3738).

The TTS was calculated by the following equation:

$$TTS\ (dB) = VPT_A - VPT_B \quad (17)$$

where, $\mathrm{VPT_A}$(dB) is the vibrotactile perception threshold after tool vibration exposure and $\mathrm{VPT_B}$(dB) is the vibrotactile perception threshold before tool vibration exposure. The experiment protocol timeline is summarised in Fig. 4.

3.3. Test procedure

Ambient temperature within the test laboratory was maintained at 20 °C ± 4 °C for the duration of all tests, verified using a Grant 2020 Series Squirrel data logger with four thermocouples. Subject fingertip temperature was measured and recorded during each TTS assessment. This was undertaken using a thermocouple attached to a digital display (RS 206–3738). If the subject's fingertip temperature was lower than 23 °C, the subject was instructed to warm their finger such that throughout the experiment, all subject's fingertip temperature was maintained at greater than 25 °C. Harada and Griffin (1991) identified the effect of skin temperature change on the TTS of vibration sense.

Annex D of ISO 5349-1 (BSI, 2001a) identifies the climatic and temperature effects of human exposure to hand-transmitted vibration in working environments. Research has demonstrated the effects of climatic conditions on the human response to vibration. Maeda et al. (1996) demonstrated the effect of low temperature on the human response to vibration. Su et al. (2016) examined the effects of high temperature on the human response to vibration. Although this research demonstrated the effects of climate condition to the human response to vibration, the results did not specifically include the hand-transmitted vibration magnitude.

ISO/CD 15230:2017 (ISO, 2017), Kaulbars (1996) and Pan et al. (2018) considered the coupling force effects in measuring hand-transmitted vibration. As shown in the factors identified in Annex D of ISO 5349-1 (BSI, 2001a), the effects of human exposure to hand-transmitted vibration in working conditions includes the coupling forces. Although they are demonstrating the effects of coupling condition changes to the human response to vibration, the results cannot include the hand-transmitted vibration magnitude in work-site conditions for reasons of practicality.

In the present study, the assumption is made that Equations (1)–(3) incorporate the factors described in Annex D of ISO 5349-1 (BSI, 2001a). The authors acknowledge that some variability in grip force will be present across the subject group. The variation in grip force has contributed to the range in apparent transmission determined by the wearable device and the human response. This variation mirrors that present in the real work site, for the purposes of illustrating a range of operating techniques. The omission of grip force control can be considered beneficial to the reported experiment. A future study to characterise the effectiveness of on subject assessment in capturing the transmission effects relative to grip force would be desirable.

Tool vibration emission was measured for 2 min using ISO 8041 compliant reference instruments; a Svantek SV106 and a Brüel & Kjær Photon + with RT Pro software. The devices were configured to obtain a continuous 2-min duration measurement. Two accelerometers were attached to the tool hand grips. A Svantek SV150 and Brüel & Kjær 4520-001 were used. Accelerometers mounting and frequency weighting filters were undertaken in compliance with ISO 5349-1 (BSI, 2001a).

Tool vibration data was obtained from a series of controlled tests performed using standard industrial power tools in a laboratory setting. Three different mechanised hand tools were used during the course of the experiment. The tools used were (1) Makita cordless drill, (2) Makita cordless drill (hammer) and (3) Ryobi mains powered (240 V 50 Hz) sander. Tools were selected to provide a range of frequency and vibration magnitudes while suitable for use in multiple postures. Tool specification and operating descriptions are provided in Table 1. The

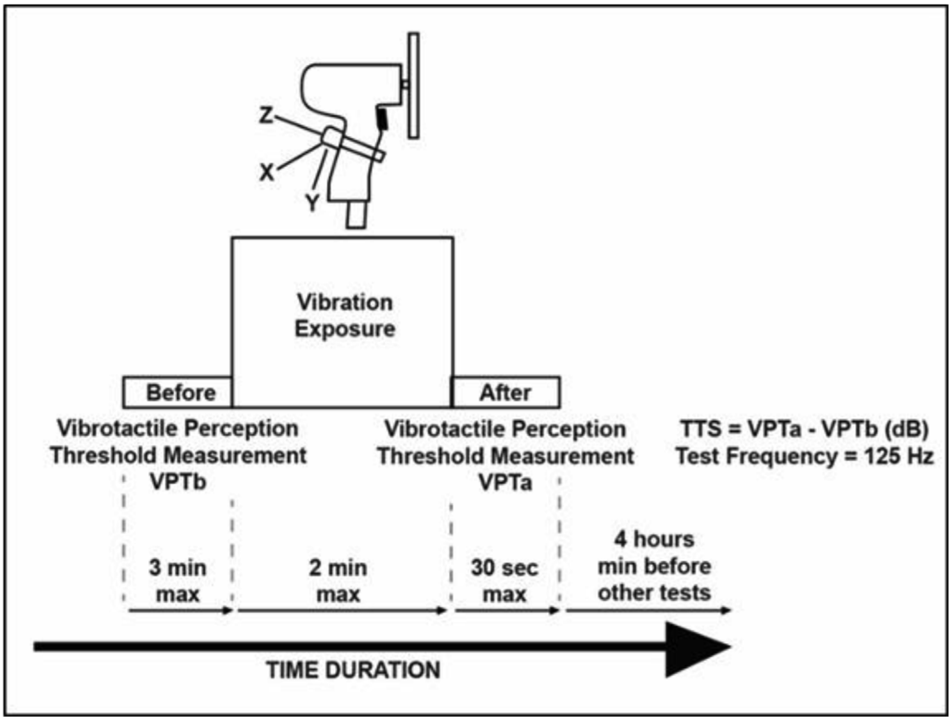

Fig. 4. Experimental protocol timeline.

Table 1
Tool description and specification.

	Tool 1	Tool 2	Tool 3
Tool description	Drill	Hammer Drill	Orbital Sander
Mechanical action	Rotary	Impact	Orbital oscillation
Load/Speed	400 rpm	6000 Blows/min	12000 Oscillations/min
Mass (kg)	1.7	1.7	1.36
Power supply	18 V Lithium-ion battery	18 V Lithium-ion battery	240 V, 50 Hz A.C.
Declared vibration (ms^{-2})	2.5	10.0	8.6
Tool age (years)	6	6	3

test duration was limited to 2 min due to the strenuous nature of the overhead posture on the subjects.

Three working postures were considered to reflect working practice. These included (1) horizontal (tool held in front of subject with both hands), (2) vertically upwards (overhead, single handed) and (3) vertical downwards (single handed). All subjects performed separate tests with each of the nine possible combinations of tool and posture configuration.

All subjects were given induction training on how to operate and grip each tool. However, subjects were not experienced tool operators and demonstrated a degree of variability in tool operation performance. Grip force was not monitored. Push force for each of the tool test activities was controlled through the use of a force plate and digital display (Kistler Type 9286B). The digital display provided real time feedback to the operator relating to the force applied in the form of a real-time graphical trace to be maintained at the predetermined force level (50 N). Subjects were given time to practice maintaining the required push force prior to commencing each tool test activity.

A reaction frame was constructed to allow 450 × 450 mm x 50 mm concrete (compressive strength, 35 N/mm^2) test panels to be mounted in the three configurations. The panels were mounted on a 15 mm steel plate with 90 × 90 equal angle sections welded to the plate to contain the precast concrete slabs. For sanding purposes, the concrete panel was removed and the sander was applied to the steel plate. The reaction frame ensured that the correct posture was attained and that structural resonance from the substrate were minimized. Subjects applied the tool to the substrate continuously, only removing it when required to start fresh hole in the substrate. Figs. 5 and 6 show the general arrangement of the reaction frame, the three posture configurations and the location of a force plate.

Simultaneous measurements were taken on the subject using a wrist mounted wearable device (HVW-001, Reactec Ltd.) and on the tool using conventional ISO 8041 compliant analysis equipment (Fig. 7) for the duration of each test.

4. Results and discussion

A total of 108 individual tests were conducted. These comprised of a single 2 min tool activity for each of the twelve subjects across the nine combinations of tool and posture. Data from six tests were omitted due to insufficient data recording, insufficient trigger time due to test

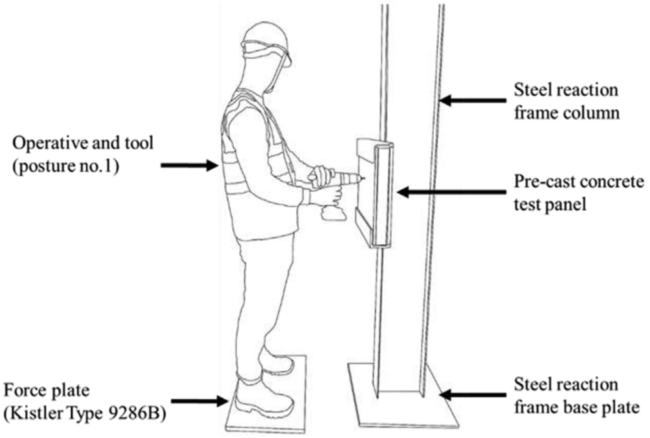

Fig. 5. Test subject, reaction frame, test panel and force plate test configuration.

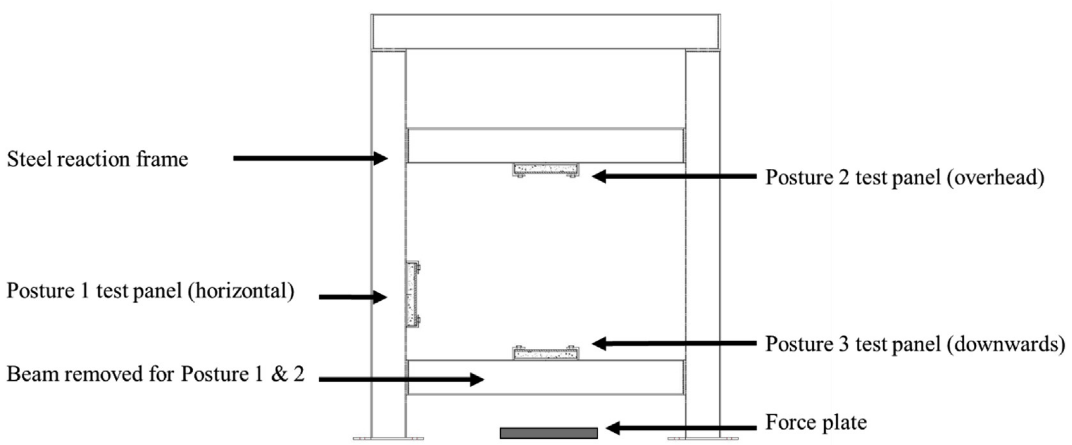

Fig. 6. Reaction frame, test panel and force plate configuration.

subject fatigue and one instance of direct contact of the wearable device with the tool. A detailed list of the data omitted is shown in Table 2.

4.1. *Validation of proposed method for hand-transmitted vibration assessment*

The test regime first seeks to validate the proposed equation (16) for data acquired on the wrist. Figs. 8–10 illustrate the frequency spectrum data for each of the three tools used in the experimental protocol under one test condition. The figures for each tool respectively compare the frequency weighted data from the on-tool instrumentation with the transformed data from the wearable device. The frequency response and magnitudes for the two methods are comparable. The data serves to support the effectiveness of the proposed methodology characterised in equations (10)–(12). The proposed wearable vibration measurement methodology is designed to correlate with conventional measurement techniques under controlled test conditions outlined within ISO 5349.

By obtaining Frequency Spectrum data using the proposed equation (16), which is consistent with the conventional vibration measurement on the tool handle, it is clear that this proposed methodology is effective in compensating for the differences between measuring at the tool/hand interface and measuring on the wrist.

4.2. *Comparison of TTS vs. tool and TTS vs. on-subject*

The test results examine the correlation of the hand-arm transmitted vibration as assessed on the human with the assessment of human response as measured by the TTS method.

Table 2
List of data omissions.

Subject	Tool	Posture	Justification
D	1	2	No measurement recorded on subject.
F	3	1	No measurement recorded on subject.
F	1	2	No measurement recorded on subject.
J	3	1	Insufficient trigger time.
H	1	2	No measurement recorded on subject.
L	3	1	Wearable device in direct contact with tool.

Fig. 11 (i) shows the relationship between TTS and the vibration magnitude on the tool handle of each subject for 1 test condition. During use of the impact drill in the horizontal position the measurement of vibration on the tool handle following the ISO 5349-2 standard is relatively consistent across all subjects while the range of human response is quite marked with a range from 15 dB of TTS to 25 dB of TTS. Previous studies (Bjerker et al., 1972; Hahn, 1966; Lundström and Johansson, 1986) have shown that when a person is exposed to hand-transmitted vibration, the TTS value increases in line with increasing tool vibration magnitude. However, within this research while the TTS is increasing across the subject pool the hand-transmitted magnitude on the tool handle is unchanging. From the results shown in Fig. 11 (i), the evaluation of hand-transmitted vibration on the tool handle is not effective in discerning the effects of the subject's interaction with the tool and supports the previously identified limitations of this approach listed within Annex D of ISO5349-1.

Fig. 11 (ii) shows a positive relationship between TTS and the on-

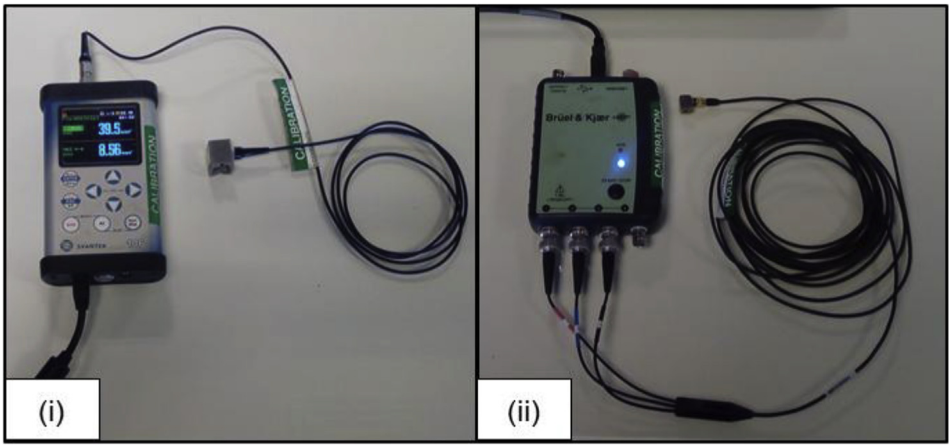

Fig. 7. Tool emission instrumentation (i) Svantek SV106 & SV 150 accelerometer (ii) Brüel & Kjær Photon+ 4520-001 accelerometer.

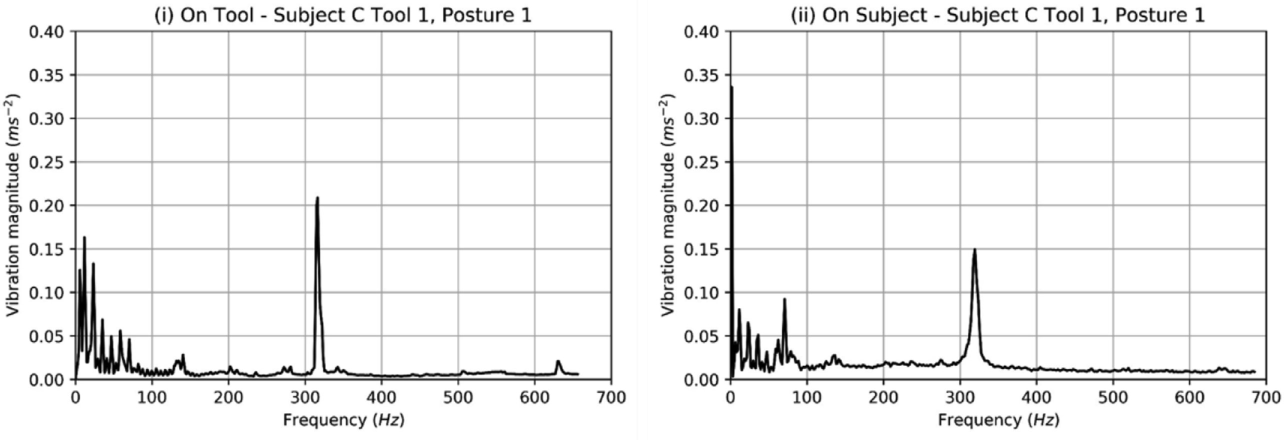

Fig. 8. Tool 1 (drill), posture 1 – (i) frequency response on tool and (ii) on subject.

subject vibration determined using the proposed equation (16). From these results, when the TTS is increasing, equation (16) vibration value is also increasing. This infers that the proposed wearable device is measuring the hand-transmitted vibration on the human including some of the affecting factors from the subject's grip on the tool handle. Despite the results being from a limited sample, the proposed consideration to measure the hand-transmitted vibration magnitude on the human is significant and worthy of further investigation. The broad range of human response, illustrated within Fig. 11 (ii), for the subject group conducting a single tool test configuration, may be indicative of factors such as operator proficiency and technique affecting the transmitted dose. A correspondingly broad range of vibration magnitudes from the on-human assessment indicates that the device is capturing the subject specific variables in vibration transmission characterised in equations (1)–(6) and (16).

Tables 3 and 4 show a summary of the test data including the coefficient of determination, Spearman rank correlation coefficient, median, standard deviation, vibration magnitude range for on tool and on subject as well as range of human response.

Regression analyses and nonparametric tests were conducted to calculate the coefficient of determination and Spearman rank correlation coefficient for TTS vs. vibration assessed on the subject and TTS vs. tool vibration emission. The results are presented showing the correlation of human response to the two methods of vibration exposure assessment. Individual analysis was considered to provide visibility of subject specific response relationships. The standard deviation across individual subject coefficients of determination for on-subject measurement is low (SD = 0.123) indicating that the relationship is stable across subjects.

A mean of all individually assessed coefficients of determination for on-subject assessment of 0.69 implied a positive linear relationship between TTS and vibration assessment on the subject is evident across the group. The measurement of vibration exposure using tool mounted accelerometers also shows positive correlation with the TTS results with a mean of all individually assessed coefficients of determination for on tool vibration assessment of 0.68.

A positive correlation ($r^2 > 0.5$) was present for all but one of the test group (Subject K, $r^2 = 0.44$) with subject C showing a particularly strong positive correlation ($r^2 = 0.908$, $\rho = 0.836$) as shown in Fig. 12.

Fig. 13 shows regression analyses for all test data. These illustrate the existence of a positive linear relationship between the TTS results and both the on-tool and the on-subject measurements.

Coefficients of determination and Spearman rank correlation coefficients were calculated for both the TTS vs. tool vibration ($r^2 = 0.695$, $\rho = 0.775$) and TTS vs. subject vibration ($r^2 = 0.606$, $\rho = 0.663$). This demonstrates that there is a positive correlation with the TTS results and that the relationship is potentially of a linear nature. The positive Spearman rank correlation coefficient values also indicate that as the vibration measurement for both on-tool and on-subject increase, the TTS increases.

Considering the data from all tests, vibration values for on-tool vibration assessment are evident over a narrow range as characterised by the clustering at three distinct vibration levels signifying the three tools under test and is not consistent with the human response. Therefore, it may be assumed that the vibration transmission through to the subject has not been fully captured and is being affected by some or all of the

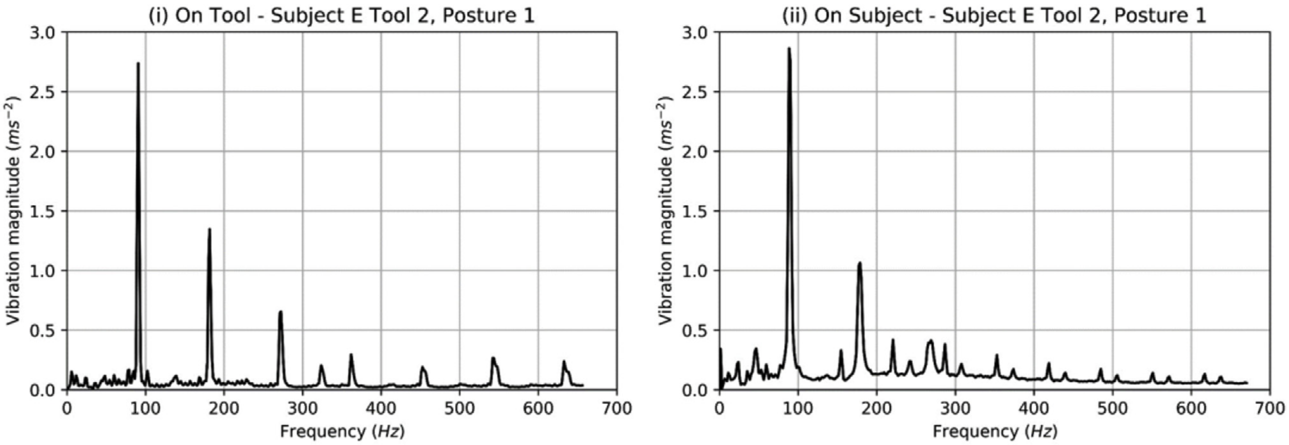

Fig. 9. Tool 2 (impact drill), posture 1 – (i) frequency response on tool and (ii) on subject.

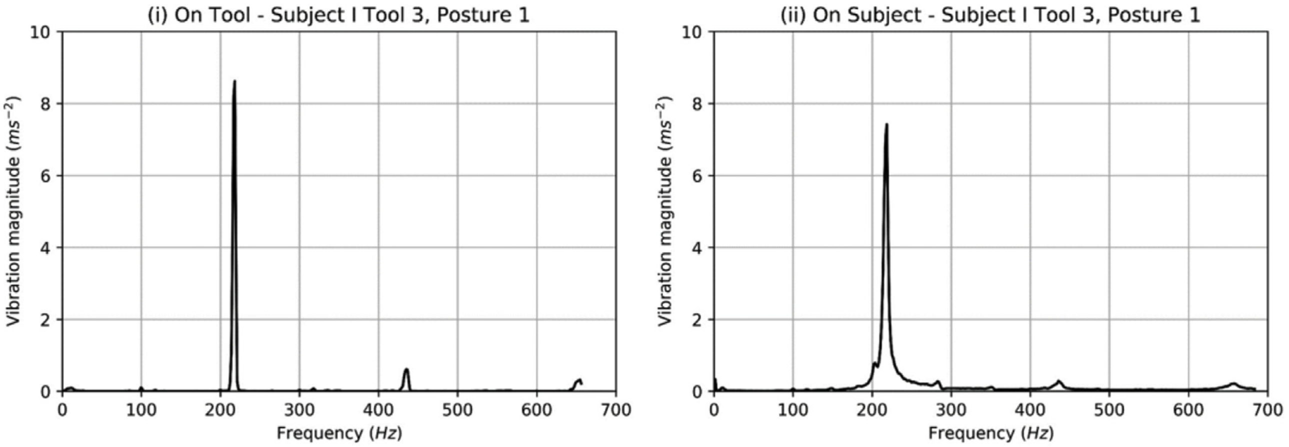

Fig. 10. Tool.3 (sander), posture 1 – (i) frequency response on tool and (ii) on subject.

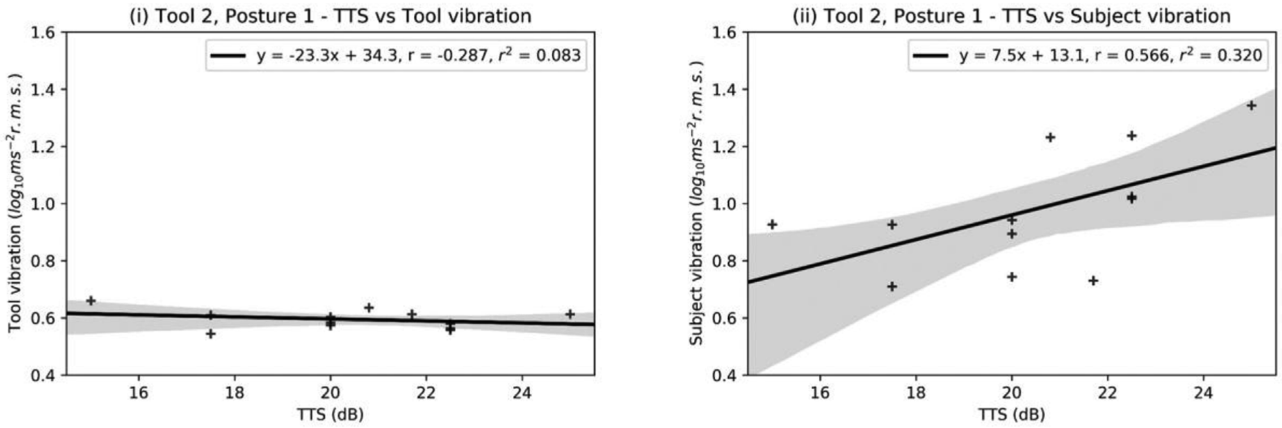

Fig. 11. Tool 2, posture 1 (i) comparison of TTS vs. tool and (ii) TTS vs. on-subject across all subjects.

Table 3
Coefficient of determination and Spearman rank correlation coefficient summary for TTS vs. on-subject vibration, a_{rhv} and TTS results.

Subject	r^2	ρ	a_{rhv} ($\log_{10}$ ms^{-2} r.m.s)		TTS (dB)	
			Min	Max	Min	Max
A	0.731	0.741	−0.058	1.339	7.5	22.5
B	0.652	0.703	−0.140	1.238	10.0	25.0
C	0.908	0.836	−0.235	1.343	10.0	25.0
D	0.595	0.439	−0.164	1.017	10.0	25.0
E	0.810	0.766	−0.044	1.284	7.5	25.0
F	0.671	0.618	−0.166	0.895	10.0	27.5
G	0.620	0.587	−0.215	1.026	7.5	22.5
H	0.739	0.602	0.084	1.089	7.5	20.0
I	0.735	0.749	−0.105	1.313	12.5	22.5
J	0.562	0.786	−0.228	1.025	10.8	25.0
K	0.440	0.712	−0.235	1.129	5.0	22.5
L	0.748	0.843	−0.157	1.276	7.5	27.5
Mean	0.684	0.698	−0.139	1.164	8.817	24.167
Std.Dev.	0.123	0.118	0.096	0.153	2.052	2.219

Table 4
Coefficient of determination and Spearman rank correlation coefficient summary for TTS vs. tool vibration, a_{hv} and TTS results.

Subject	r^2	ρ	a_{hv} ($\log_{10}$ ms^{-2} r.m.s)		TTS (dB)	
			Min	Max	Min	Max
A	0.867	0.877	−0.277	1.028	7.5	22.5
B	0.639	0.737	−0.372	1.109	10.0	25.0
C	0.767	0.726	−0.372	1.109	10.0	25.0
D	0.687	0.756	−0.275	1.091	10.0	25.0
E	0.691	0.592	−0.332	1.084	7.5	25.0
F	0.634	0.873	−0.299	1.118	10.0	27.5
G	0.924	0.966	−0.312	1.129	7.5	22.5
H	0.649	0.822	−0.387	1.142	7.5	20.0
I	0.569	0.698	−0.297	1.022	12.5	22.5
J	0.540	0.786	−0.332	1.129	10.8	25.0
K	0.620	0.698	−0.341	1.068	5.0	22.5
L	0.729	0.928	−0.325	1.076	7.5	27.5
Mean	0.693	0.788	−0.326	1.092	8.817	24.167
Std.Dev.	0.114	0.109	0.037	0.039	2.052	2.219

variables outlined within Annex D of ISO 5349-1. The on-subject assessment illustrates a similar range of human response to vibration but does not show the same grouping of a limited range of vibration magnitudes across a wide range of human response. The results indicate that with the large data set of all variables between individuals, tool types and postures there remains an unidentified variable, perhaps an element of control in the tool's use, which is influencing the human response.

The analysis of the test data shows that there is a positive linear relationship between TTS and on the tool vibration when reviewing the full data set. These results are consistent with those reported by the UK Health and Safety Executive (HSE) in relation to TTS and on tool acceleration data (Poole and Mason, 2006). However the range of human response present within a specific tool test activity across a range of operators and the wider effects of extending a specific tool to multiple postures are not consistent with the on tool vibration assessment data.

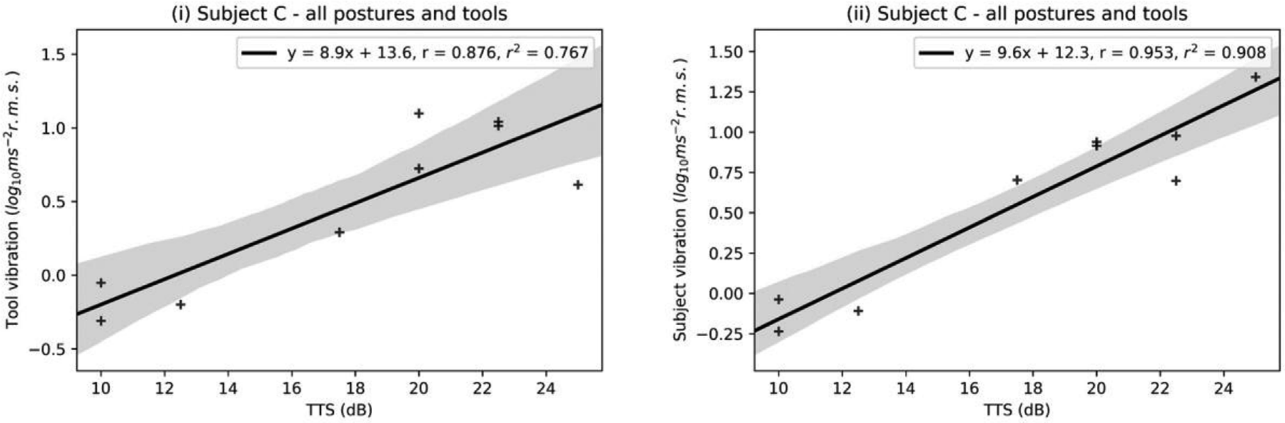

Fig. 12. Subject C (i) TTS vs. tool and (ii) TTS vs. on-subject results.

The results for an individual test condition indicate that the measurement on the tool is not effective in discerning the effects of the operative's physical interaction and supports the previously identified limitations of this approach listed within Annex D of ISO 5349-1. Although characterisation of the vibration exposure currently uses the acceleration of the surface in contact with the hand as the primary quantity, it is reasonable to assume that the biological effects depend to some extent on the coupling of the hand to the vibration source. The results of this study support such a hypothesis.

The effect of different postures for on tool vibration assessment appeared minimal as evidenced by the separation of test data into just three distinct groupings seen in Fig. 12. These represent the three different tools in use but with no further delineation evident that might signify the effect different postures have on the transmitted vibration.

A positive linear relationship does exist between TTS and on-subject hand-transmitted vibration assessment indicating that assessment on the subject would also be a useful indicator of potential harm. With a positive linear relationship for on-subject assessment being evident, the analysis of specific tool tests indicates that the on-subject assessment is indicative of harm specific to the individual operator by capturing the effects of the operative's interaction with that tool.

A low standard deviation across individual subject correlation coefficients for the on-subject assessment indicates that the relationship between exposure assessed on the subject and the human response is stable across a group of test subjects. This is deemed significant as the suitability of such a wearable device for assessing risk in real work environments requires that its ability to accurately assess potential harm to the individual is not subject specific.

Effects of different posture on vibration assessed on the subject were evident in the results, however, the effects were not uniform across the subject group. This may be due to a lack of experience in mechanised tool use among the subjects resulting in a different level of proficiency in different postures.

In addition to the limitations of on tool assessment identified within this study, existing literature (CEN/TR 15350) has demonstrated the challenges associated with ISO 5349-2 (BSI, 2015) compliance in performing *in-situ* measurements of vibration exposure from workplace tools. Measurement in accordance with ISO 5349-2 requires trained technicians to undertake such work using compliant apparatus. Risk assessment often relies upon a single point in time hand-transmitted vibration on-tool measurement. This value is often assumed from manufacturers declared emission data rather than conducting field measurements following ISO 5349-2. The use of such data can potentially underestimate an individual subjects' response to vibration exposure. This uncertainty has been identified by governing bodies as a concern when considering *in-situ* work practice (HSE, 2005). The existence of positive correlation between on subject monitoring and the human response across individual subjects using a range of tools and working postures supports the use of such a sensor for practical *in-situ* vibration exposure assessment.

5. Conclusions

In the current study, an experiment was performed to clarify the effectiveness of the consideration of a proposed hand-transmitted vibration measurement on the human. From these experiments, the following conclusions were drawn:

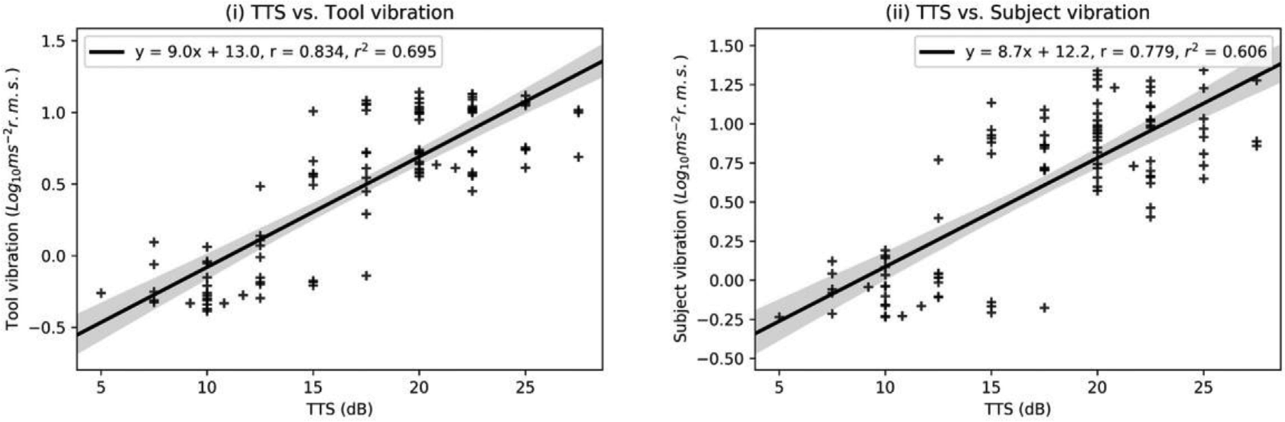

Fig. 13. TTS vs. tool and TTS vs. on-subject vibration (all data).

1. The results show that data acquired on the human using a wrist worn wearable device, with the proposed methodology, can be used for determining hand-transmitted vibration with enough accuracy to predict exposure risk.
2. The research has demonstrated that the principle of utilising hand-transmitted vibration as an indicator of HAVS health risk is valid and can address a number of limitations identified with the use of tool emission data.
3. The results also provide evidence of the on-tool vibration assessment failing to fully capture the physical interaction of the operative with the tool and consequently not capturing the full range of human responses possible from a range of operators operating a specific tool in a variety of applications.
4. The research demonstrates that hand-transmitted vibration assessed on the human can capture effects of transmission and tool interaction specific to the individual operator which directly affects the risk faced and are not captured with tool emission data.
5. The test results demonstrate that the assessment of vibration transmitted to the tool operator using a wearable device of the proposed methodology is positively correlated with the human subjects' response to vibration.
6. It was clarified that by addressing the limitations identified within Annex D of ISO 5349-1 using on-subject in-situ assessment of vibration by the proposed methodology over a period of time, the proposed method may be used to make a representative assessment of the risk faced by an individual.

The conducted tests have provided a comparative study of vibration exposure measurement techniques and suggest that greater consideration should be given to the proposed wearable devices methodology as a practical workplace solution to vibration monitoring. Further experimentation using different tool types, operatives with previous experience of using hand-held power tools and on-site live working environments should be considered. Further research to examine operator physiology and biodynamics is required to fully understand the response of structures within the hand and arm to mechanical vibration.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ergon.2019.01.002.

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