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Human machine interactions and the human response to vibration

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ABSTRACT

Prolonged occupation exposure to a vibration source at the hands can result in a disease known as hand-arm vibration syndrome. As the condition is irreversible, all current efforts to combat this disease involve the reduction of vibration exposure through risk assessment and health surveillance of those at risk. The current standard for vibration assessment (ISO 5349) introduced a method of vibration measurement based on the placement of sensors on the tool handle, however a multitude of factors recognised within the standard exist which can affect actual vibration exposure to the individual. This study investigates the effect of one of these factors; operator posture, its impact on hand transmitted vibration and the relationship between the assessment method and an evaluation of the human response to that vibration. By evaluating the human response to vibration and complementing the standardised method with a wearable sensor device, the authors demonstrate the effects of posture on human vibration exposure in a typical civil engineering application and evaluate the relative significance of this phenomenon in different scenarios.

1 INTRODUCTION

Hand-arm vibration syndrome (HAVS) is an industrial disease caused by prolonged exposure to a source of vibration affecting the hands of an individual, such as sustained occupational exposure to mechanised vibrating tools. This condition manifests with neurological, vascular and musculoskeletal symptoms. Some of the most characteristic symptoms include finger blanching, pain, loss of dexterity, numbness, dysesthesia and paraesthesia. (Mansfield, 2004).

HAVS presents itself as a progressive and irreversible condition, and as such, prevention and accurate assessment of exposure constitute the only tools currently available to deal with the disease. As a condition predominantly linked to occupational exposure, the currently established method for assessment of the vibration exposure and disease progression is standardised and contained in the ISO 5349 document (International Organization for Standardization, 2001a). Following this standard, vibration exposure is assessed based on determining the duration of exposure and through the placement of sensors on the tool handle to measure acceleration magnitude at this position. This measurement is commonly accepted as the hand-arm vibration magnitude and used as a unique magnitude (together with exposure time) to assess the risk perceived by a tool operator.

1.1 Factors affecting vibration exposure and posture effects

However, clause 4.3 of ISO 5349-1 states that although the standardised method of vibration assessment involves the measurement of vibration at the tool surface, it is reasonable to assume that the resulting biological effects depend to a large extent on the coupling between the hand and the vibration source.

Furthermore, Annex D in the same document acknowledges and identifies the presence of multiple factors that affect the exposure to hand-transmitted vibration in the real work environment. Some of these factors include the direction of the vibration, skill and working method, individual constitution, hand and body posture, or coupling forces. In order to achieve an accurate assessment of vibration exposure, the contribution of these factors will have to be characterised and fully understood.

This study focuses on determining the effect of posture on the vibration exposure to the operator in an applied environment where desired posture may be affected by other factors such as operator physiology. With the incorporation of some of the known limitation outlined within Annex D by replicating a real work environment for the experiment the authors seek to illustrate their significance in the context of risk management. To evaluate both the effect on tool emitted vibration and the effect on vibration transmitted to the individual it is desirable to include both a standardised on-tool measurement in accordance with ISO 5349 and a modern wearable sensor, worn on the subject.

The motivation to consider a wearable device within the study arises from the commonly accepted notion that the standard method for calculating exposure requires a skilled technician and a controlled environment to execute a repeatable assessment. In practise, a measurement spanning minutes is unlikely to capture the variability in day-to-day tasks undertaken by tool operators in different activities and industries. The CEN technical report CEN/TR 15350 (British Standards Institution, 2013) identifies the difficulty in capturing all the factors affecting the vibration level of a tool and recognise the expense of doing so, advising that a range of factors would need to be considered to make an ideal assessment of vibration exposure.

1.2 Vibrotactile perception threshold

Vibrotactile perception threshold (VPT) is defined in ISO standard 13091-1 (I. International Organization for Standardization, 2001) as the skin surface acceleration capable of triggering a 50% response rate for detection by the individual. This minimum threshold for detecting vibration in the fingertip has often been used as a diagnostic technique to assess neurological damage in HAVS (Radziukevich, 1969).

Existing research links the temporary threshold shift (TTS) in the VPT after short durations of acute vibration exposure with the long-term permanent threshold shift that would develop over a longer period of time with a similar exposure (Malinskaya et al., 1964). For this reason, TTS may be used as an indicator of risk to the human subject arising from interaction with a specific vibration source.

Based on this body of research, TTS is used during the present study as an indicator of the human response to a period of vibration exposure. Vibration measurements, both at the tool and on the subject, will be compared with this indicator to determine the effectiveness of such methods at predicting the human response to the vibration and the potential risk for HAVS development.

2 MEASUREMENT OF HAND-ARM VIBRATION ON THE SUBJECT

The wearable device used in the study (HVW-002, Reactec Ltd.) is mounted in the wrist of the subject by means of a nylon webbing strap and adjusted using a velcro arrangement in the strap. The orientation of the device is controlled by aligning the flat surface of the device with the wrist of the operator, in such a direction that the wearer will be able to read the display on the device.

This device includes a triaxial accelerometer, implemented through a MEMS device (LIS3DSH, ST Microelectronics). The operation range of this accelerometer is limited to ±8g, and the recommended temperature range is -40ºC and +85ºC.

This accelerometer captures the vibration on the wrist at a sampling frequency of 1.6kHz, to allow for a total captured frequency range between 0Hz and 800Hz. 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. At the specified sampling frequency of 1.6kHz, 1024 samples are captured in a total of 0.64s. Samples are captured in cycles of 1.5s, and the remaining 0.86s are used by the device to process the previously obtained sample.

The 1024-point FFT results in a total of 512 power spectrum coefficients in the 0-800Hz frequency range. However, only data within the 0-650Hz is processed, discarding the coefficients 417 to 512. In equations 1 to 3 the coefficient ‘i’ represents the frequency coefficient index, with values between 0 and 416. Conversely, the coefficient ‘n’ represents each of the samples, one captured every 1.5s, which increases in relation to the total duration of the tool vibration recording.

For each sample, the sum of the frequency weighted FFT magnitude values for each of the axes is calculated, using equations 1 to 3 for each (n) frame:

$$a_{rhx}(n) = \sqrt{\sum w_{rhx}(i)^2 \cdot a_{hx}(n,i)^2} \tag{1}$$

$$a_{rhy}(n) = \sqrt{\sum w_{rhy}(i)^2 \cdot a_{hy}(n,i)^2} \tag{2}$$

$$a_{rhz}(n) = \sqrt{\sum w_{rhz}(i)^2 \cdot a_{hz}(n,i)^2} \tag{3}$$

Where w_{rhx}, w_{rhy} and w_{rhz} are frequency weighted transfer functions specifically designed to account for the transmissibility of the hand-wrist system and replicate the ISO 5349-1 weighting function. $a_{hx/y/z}$ defines each of the 417 coefficients that belong to a given frame, which are weighted and combined to obtain a unique magnitude $a_{rhx/y/z}$ for each axis. These transfer functions were determined by the manufacturer in a separate piece of research. (Maeda et al., 2019).

For each of the three axes, a running average is determined independently after each frame *n*, using the equations 4 to 6, respectively:

$$a_{rhx} = \sqrt{\frac{\sum_n a_{rhx}(n)^2}{n}} \tag{4}$$

$$a_{rhy} = \sqrt{\frac{\sum_n a_{rhy}(n)^2}{n}} \tag{5}$$

$$a_{rhz} = \sqrt{\frac{\sum_n a_{rhz}(n)^2}{n}} \tag{6}$$

Finally, the running averages of the three axes are combined using equation 7, in order to determine the overall vibration magnitude over the duration terminated by (n):

$$a_{rhv} = \sqrt{a_{rhx}^2 + a_{rhy}^2 + a_{rhz}^2} \tag{7}$$

3 EXPERIMENTAL METHODOLOGY

3.1 Test Subjects

In order to study the effect of vibration on the human body, a total of 12 male subjects with no previous history of vibration exposure participated in the study. All participants were non-smokers with an age range restricted between 18 and 24 years of age to minimise the effect of age on subject response to vibration (Venkatesan et al., 2015). In accordance with ISO 13091-1 (I. International Organization for Standardization, 2001), the participants were not allowed to smoke, consume caffeine or alcohol during the duration of the experiment.

All participants wore steel toe-capped safety boots with a rubber outsole, complying with ISO 20345:2011 (International Organization for Standardization, 2011). In order to minimise additional factors affecting the human-tool interface, no gloves were worn during the tests. 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 Vibrotactile temporary threshold shift

TTS is defined as the difference, expressed in dB, in the vibrotactile threshold before and after exposure to vibration (Maeda and Griffin, 1993; Yonekawa et al., 1998). Testing was limited to two sessions per day for each operator, in order to allow a minimum of 4h of rest between each test. The expression used to calculate TTS was:

$$TTS\ (dB) = VPT_A - VPT_B \tag{8}$$

Where VPT_B corresponds to the baseline vibrotactile perception threshold before the vibration exposure and VPT_A is the vibrotactile perception threshold after the exposure.

Vibrotactile sensitivity VPT_B was obtained 3 min prior to the start of the tool activity, and VPT_A within 30 seconds after the test was completed. A vibrotactile sensation meter (RION type AU-02A) was used for the assessment of the vibrotactile perception threshold, by delivering pulses of 125Hz and varying intensities to the tip of the index finger. To ensure consistency, subjects were asked to maintain a constant force of 2N with their index finger, as measured using a digital scale connected to a display. VPT was determined by gradually adjusting the intensity of the pulses, and recording the minimum intensity at which the stimulus became perceptible. Three measurements were obtained within a 30 second frame, and the final result for each individual and test is obtained by averaging these three results.

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. The effect of fingertip temperature has been previously characterised by previous research (Harada and Griffin, 1991), and should be kept constant to avoid external variance in the results.

3.3 Test procedure

In order to study the effects of posture on vibration exposure, a total of 8 test conditions were considered, composed by the combination of 4 tools and 2 working postures. The tools used to generate the vibration exposure during the study and their relevant mechanical properties are detailed in Table 1. All of these tools are rotary demolition hammers, used in their hammer drill configuration to produce holes in a block of concrete.

Table 1: Tools used in the experiment

	Tool 1	**Tool 2**	**Tool 3**	**Tool 4**
Manufacturer	Makita	Makita	Milwaukee	Bosch
Model	HR4011C	HR4011C	Kango 950 SDS	GBH 11 DE
Blows per minute	1350	2750	1950	2250
Mass [Kg]	6.3	6.3	11.8	11.1
Declared vibration magnitude [m/s^2]	4.5	4.5	11.0	24.0
Declared uncertainty [m/s^2]	1.5	1.5	2.0	1.5
Blow energy [J]	6.2	6.2	20	18

The two working postures considered are depicted in Figure 1. The first posture involves drilling downwards into a block of concrete, with the weight of the tool resting on the drill bit and the operator merely guiding the tool. The second posture involved drilling horizontally into concrete, with the weight of the tool born by the operator and significant force applied against the substrate in order to maintain the hammer action.

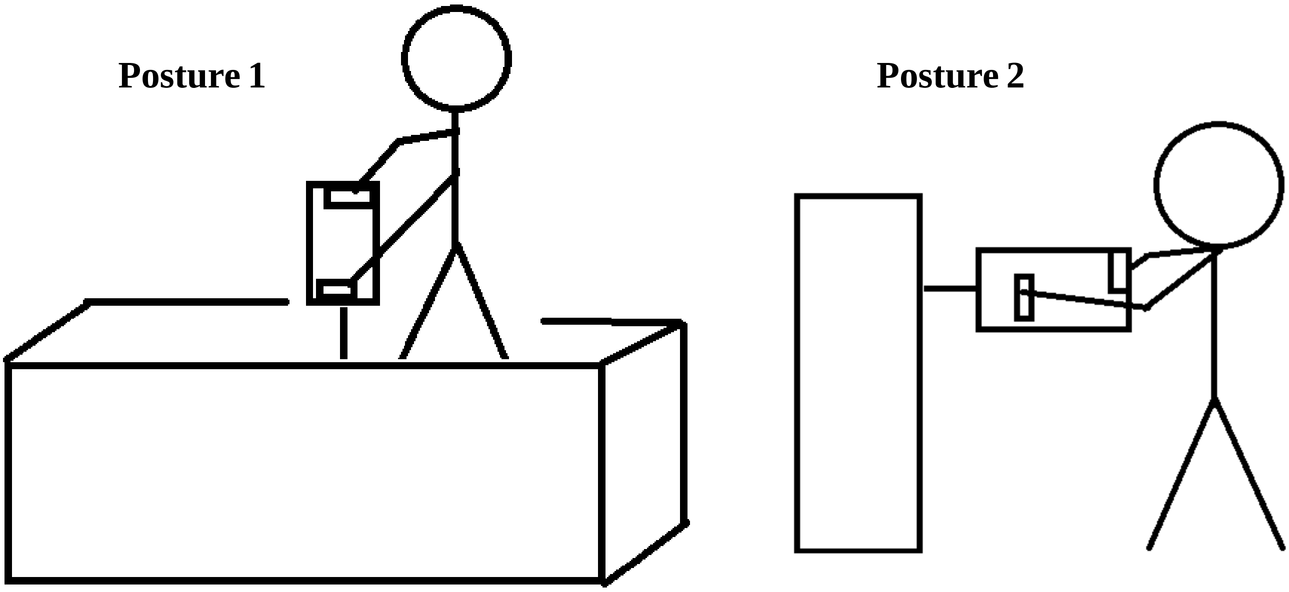

Figure 1: Working postures studied during the experiment. Posture 1 (left) involved vertically drilling into a block of concrete, while Posture 2 (right) had the operator drilling horizontally.

Vibration data was obtained from accelerometers mounted on the tool handle, according to the specifications of ISO 5349-1 and ISO 5349-2 (International Organization for Standardization, 2001a, 2001b), and the obtained signals were processed in compliance with the standards. Two sensors were used: a Svantek SV106 and a Brüel & Kjær 4520-001, both compliant with ISO8041 standard (International Organization for Standardization, 2005). Furthermore, the subjects wore a wrist mounted wearable device (HVW-002, Reactec Ltd.) to capture vibration data concurrently with the on-tool sensors.

A test was performed for each of the participants, and each of the tool/posture combinations. The test procedure for each one of the individual tests is depicted in Figure 2. Vibrotactile perception was assessed 3 minutes prior to the vibration exposure, and subjects were instructed to operate the corresponding tool in the indicated position for a total of 2 minutes continuously. Within 30 seconds of finishing the tool operation, the VPT of the subject was measured again. In order to avoid interference between tests. A minimum of 4 hours was allowed between two tests for any given subject.

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.

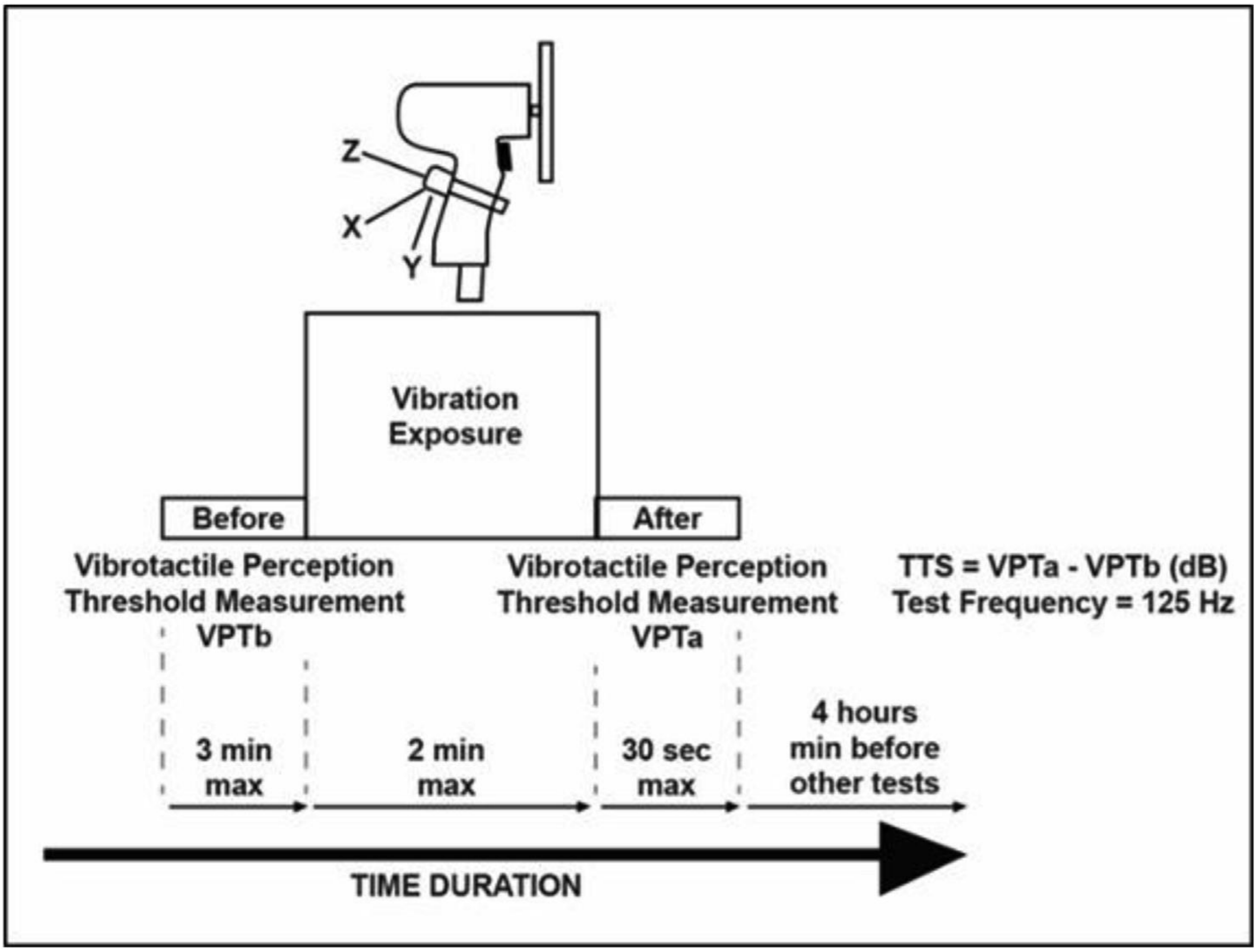

Figure 2: Test procedure sequence for each of the individual tests. One test was performed for each of the subjects, and each of the tool/posture combinations

4 RESULTS AND DISCUSSION

With 12 participants each performing tests with 4 tools in two separate body postures, the total number of tests conducted for the experiment was 96. Two tests were discarded from further analysis due to displacement of the sensors on the tool handle. Every test included two minutes of continuous tool operation, preceded and followed by measurements of VPT. All of the vibration results obtained are detailed in Table 2.

Table 2: All results obtained during the study, grouped by posture and tool.

		On-tool vibration [m/s^2]		**On-subject vibration [m/s^2]**		**TTS [dB]**	
		Mean	**S.D.**	**Mean**	**S.D.**	**Mean**	**S.D.**
Tool 1	**Posture 1**	5.3	0.6	7.3	1.9	13.3	1.6
	Posture 2	5.5	0.7	8.0	1.6	14.0	3.1
Tool 2	**Posture 1**	9.0	0.9	10.4	1.8	14.2	2.7
	Posture 2	8.3	1.5	10.9	1.9	14.7	2.1
Tool 3	**Posture 1**	15.6	2.0	19.0	4.0	16.6	4.0
	Posture 2	10.6	1.3	14.7	3.9	12.7	2.9
Tool 4	**Posture 1**	17.3	1.9	24.9	5.0	16.0	3.2
	Posture 2	12.2	2.0	19.7	5.3	14.1	2.5

4.1 Inter-operator effects on vibrations

One of the primary motivations for adoption of monitoring technology capable of gathering data on an individualised fashion lies in the limitations of using a single vibration magnitude value to accurately predict vibration exposure. Whether the applied vibration magnitude value comes from a manufacturer declared value or from an ISO 5349-1 compliant measurement, it is hypothesised that this value will be hard to extrapolate to every scenario in a work environment. Factors likely to preclude such an effective extrapolation are in fact listed within Annex D of ISO 5349-1. In particular physicality and technique of the operator is listed as likely to affect the vibration transmitted to the individual.

Figure 3 offers a graphical representation of the vibration magnitude distributions obtained for each tool across the cohort of operators. Both measurement methods, on the tool and on the subject reveal a spread in the vibration magnitudes detected. It can be observed that for each of the tools, the emitted vibrations fall within a wide range instead of a single constant value. There is a notable difference between tools 1 and 2, with a lighter weight, lower energy output and easier operation; and tools 3 and 4, heavier, more powerful and more technique dependent. This is noteworthy as the investigators selected tools which were broadly considered to be similar and would all be considered suitable for the test activities and could reasonably have been hired under the same class of tool from tool hire centre. In the case of the first two tools, the spread observed is narrower, which combined with overall lower vibration magnitudes translates into a reduced risk of incorrect vibration estimation. However, the heavier and higher impact energy tools 3 and 4 show a large spread between operators, combined with higher overall vibration magnitudes. In both tools, regardless of the measurement method, the operator with the highest vibration levels is exposed to more than twice the vibration magnitude received by the operator with the lowest vibration.

These results reveal the difficulty of accurately assessing the exposure risk which a tool operator may be exposed by using a single magnitude for a given tool, and the potential advantage of real time vibration assessment on an individual basis.

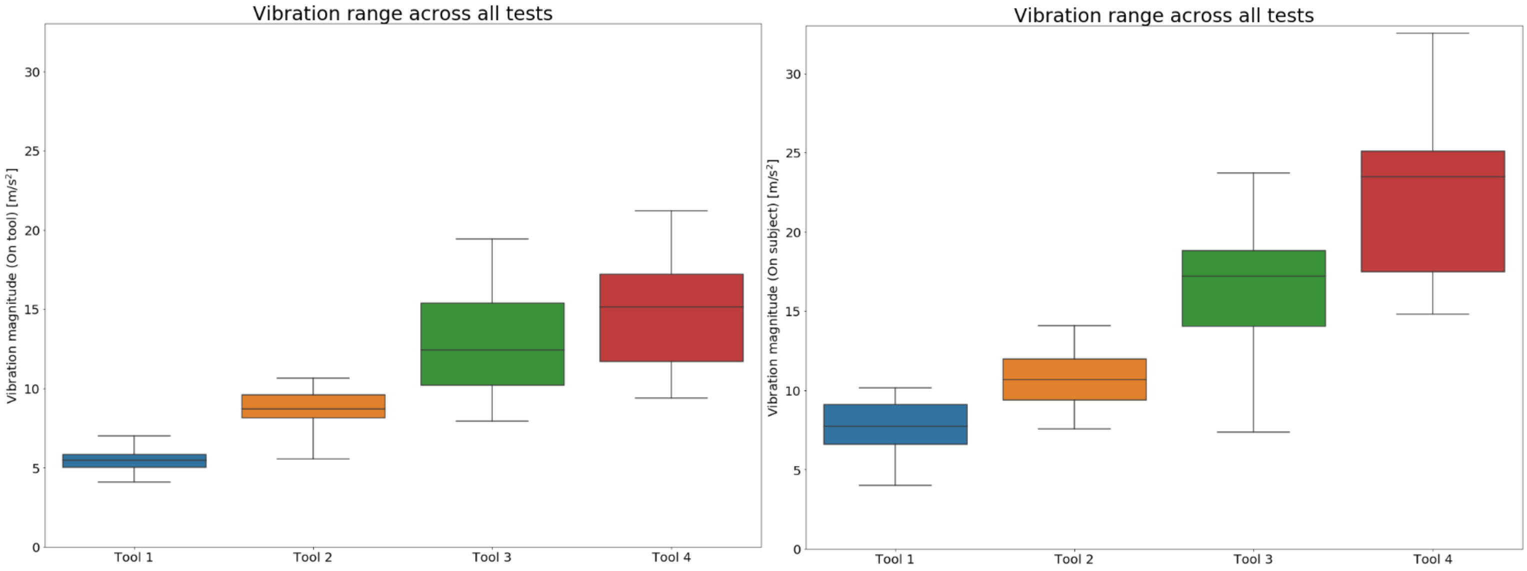

Figure 3: Inter-operator vibration distributions for all tests, expressed in the form of boxplots for each of the tools used in the experiment. To the left, the vibration values obtained from the tool handle. On the right, the same results obtained using a wearable device.

4.2 Effect of posture on vibration magnitude

The obtained results were analysed to determine how a change in working posture affects the vibration levels that affect the operators. The distribution of vibration magnitudes, categorised by tool and posture, is illustrated in Figure 4.

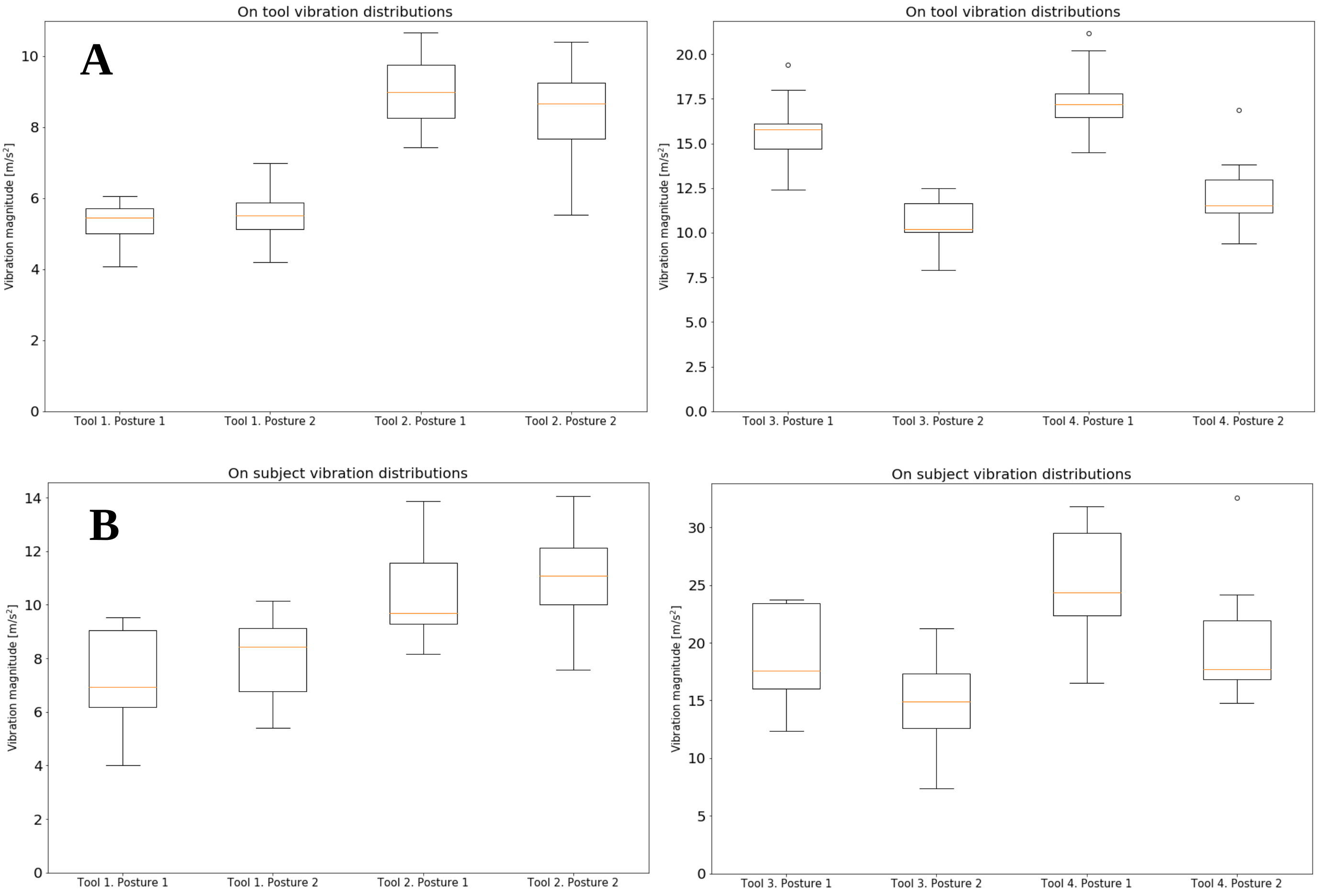

Figure 4: Vibration magnitude distributions for each of the tools and operator postures, as measured (A) on the tool handle and (B) on the subject wrist.

When comparing the vibration magnitudes for each of the postures, some effects become evident. The first consideration is that, for a given tool, there are significant changes in the vibrations produced depending on the operator posture. Moreover, both measuring techniques are capable of detecting these changes in vibration magnitude. These findings reinforce the ideas included in Annex D of ISO5349-1 and challenge the validity of a single magnitude value for accurate risk assessment of the operators. Existing research (Maeda and Shibata, 2008, 2007) studying the effect of posture on human physiological response to vibration is consistent with these results, and found that operator posture can translate into changes in hand-transmitted vibration.

A second interesting result concerns the specific direction of change with the posture. For tools 1 and 2, lighter and easier to use, the transition between a downward posture (posture 1) and a horizontal posture (posture 2) translates into an increase in the vibration generated by the tool. The exception of on-tool measurements for tool 2 will be discussed in the following section. In contrast to this trend, the heavier tools 3 and 4 show an inverse pattern. The transition between the downward posture and the horizontal posture translates into a decrease in the measured vibration. The significance of this finding lies in the fact that the interaction between posture and vibration is not unique or easily predictable. This is relevant in the eyes of the investigators as it will preclude any attempt to account for posture effects when basing any risk assessment on a fixed vibration value.

Finally, it is interesting to study how these changes in vibration magnitude translate into the work exposure of an operator. When considering the changes in vibration magnitude due to posture, as measured on the subject, the change from the vertical to the horizontal posture translates into a -4.6% change in the time required to achieve an A(8) level of 2.5m/s^2 for Tool 1, and +14.4% for Tool 2. While these may not heavily alter acceptable work period for an operator, when observing the heavier tools and the same change in posture, the time required to reach an A(8) level of 2.5m/s^2 is reduced by -53.8% with tool 3 and -50.8% for tool 4, reducing the potential work performance of an operator by more than half. The presented changes in operation time have been calculated based on On Tool magnitude values, but very similar results are obtained when considering On Subject measurements. These significant results, which are illustrated in Figure 5, reveal that accurate knowledge of the effects of posture on operator exposure to vibration can be crucial both in ensuring operator health and maximising worker productivity.

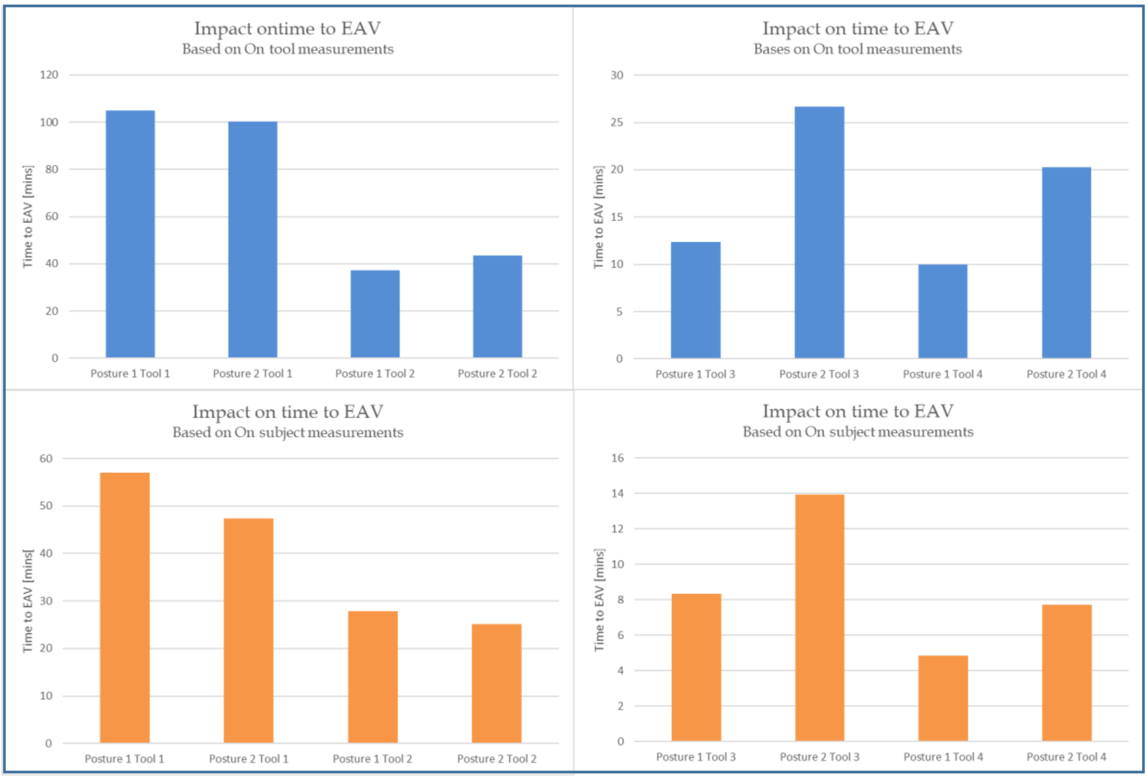

Figure 5: Changes in work time to EAV when considering different tools and both On Tool and On Subject measured vibration magnitudes

4.3 Posture effects on human physiological response

In this study, the human response to vibration is assessed through testing of the temporary threshold shift (TTS) of the vibrotactile perception threshold (VPT). This test has for decades been established as a method to determine the energy absorbed by the operator and to diagnose the risk for long-term neurological damage (Malinskaya et al., 1964; Radziukevich, 1969).

The vibration magnitude measurements for each tool/posture combination were compared against the obtained TTS after their respective tests, and are detailed in Figure 6.

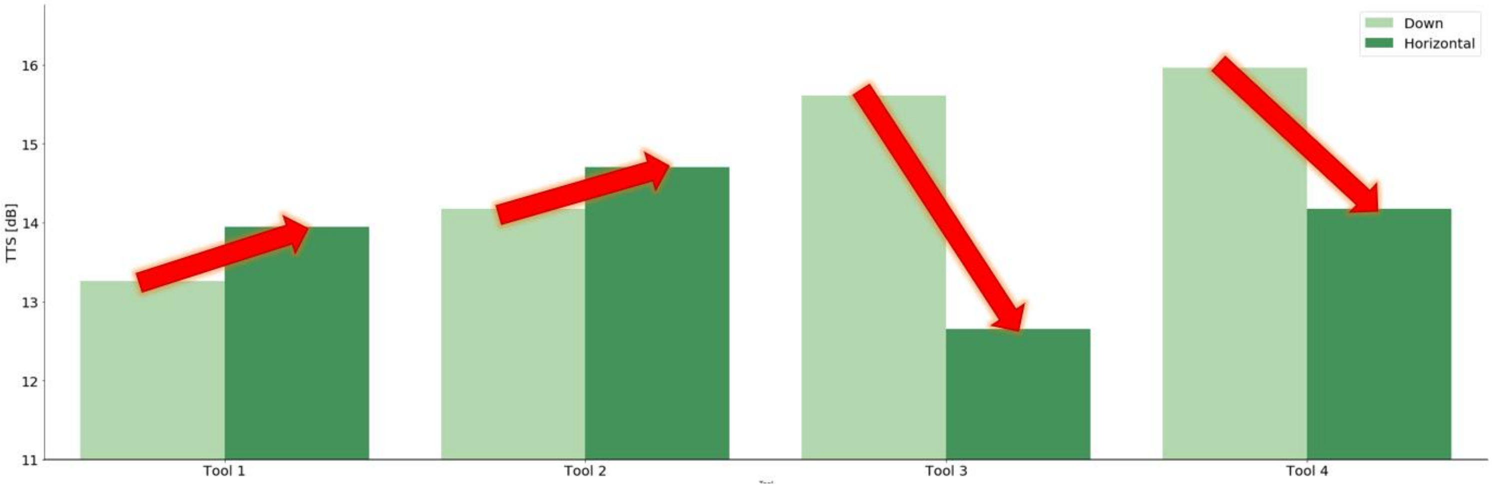

Figure 6: TTS measurements (mean) across the different test configurations.

These results evidence a high degree of correlation with the vibration measurements discussed in previous sections. Firstly, significant differences in human response can be observed when transitioning between postures. This indicates that the observed differences in vibration are representative of the physiological effects these vibrations have on the subject, confirming the effect of posture in the risk of HAVS development.

Secondly, the trends revealed in human response match the observation made at a vibration level. For tools 1 and 2, a change from a downward (posture 1) to a horizontal (posture 2) position increases the vibration levels received by the operator. A notable exception lies in the vibration emitted by tool 2, which in the case of on tool measurements failed to capture the trend, unlike on subject measurements. Conversely, in tools 3 and 4 the opposite trend is present, with reduced vibration exposure when transitioning between postures. Again, this finding is significant as it precludes the ability to predict the effect of posture without specific assessment but does validate the use of real time vibration assessment as an effective indicator of risk.

4.4 Validity of on-tool and on-subject vibration measurement to capture posture effects

Considering that the transfer function included in the wearable device was originally designed to correlate with ISO-5349 measurements due to existing human research being based on this standard, it is expected for both techniques to yield similar results. Figure 7 confirms this tight relationship between both sets of results. However, it can be observed that while the correlation between both results in Posture 1 is very high (Pearson’s correlation coefficient = 0.92), this relationship becomes more spread when considering Posture 2 (Pearson’s correlation coefficient = 0.74). It is argued that in a simpler position like the vertical posture, in which the transmission of vibration from the tool to the hand-arm system is likely to be affected by less factors, both measurements are expected to yield similar conclusions. However, these results may vary when moving to a horizontal position, more complex to execute and offering a less direct transmission from the tool to the hand-arm system. In this case, as shown by the posture transition in Tool 2, the on-tool measurements may not accurately capture the trends observed in TTS tests and therefore the correlation with on-subject measurements could decrease.

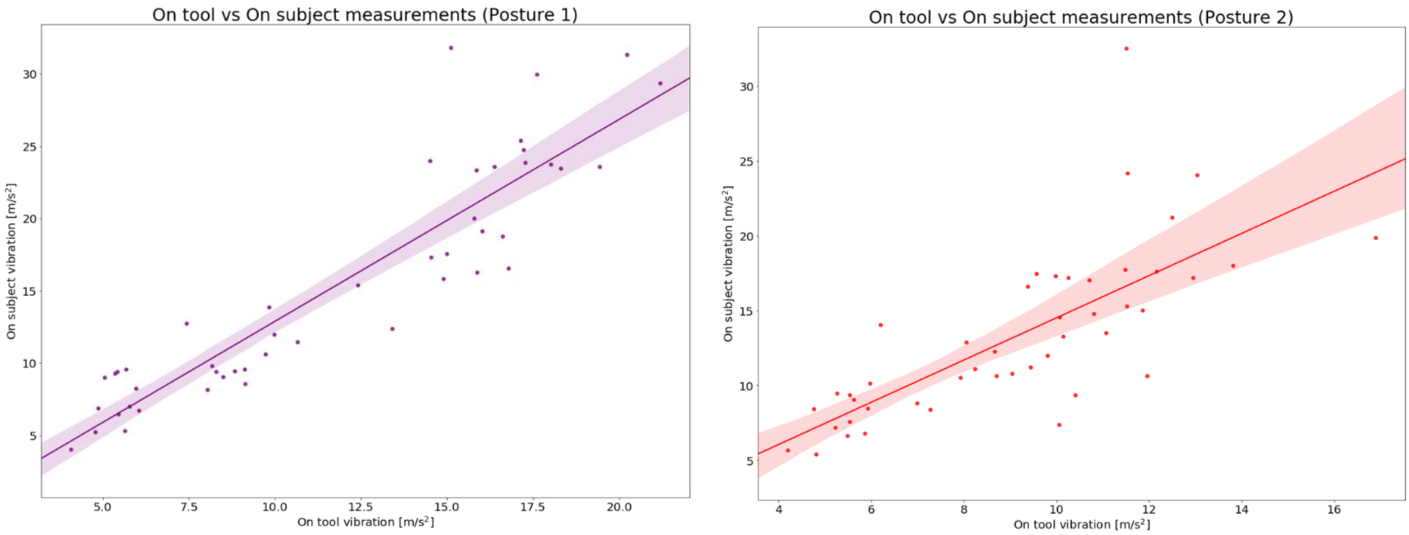

Figure 7: Comparison between the on-tool and on-subject measurements for each of the tests, for both postures.

When comparing both sets of results against their corresponding TTS measurements, results for human response in the form of TTS of the VPT seem to mirror the detected changes in vibration emission. When both sets of results are represented together, in Figure 8, the relationship becomes clear.

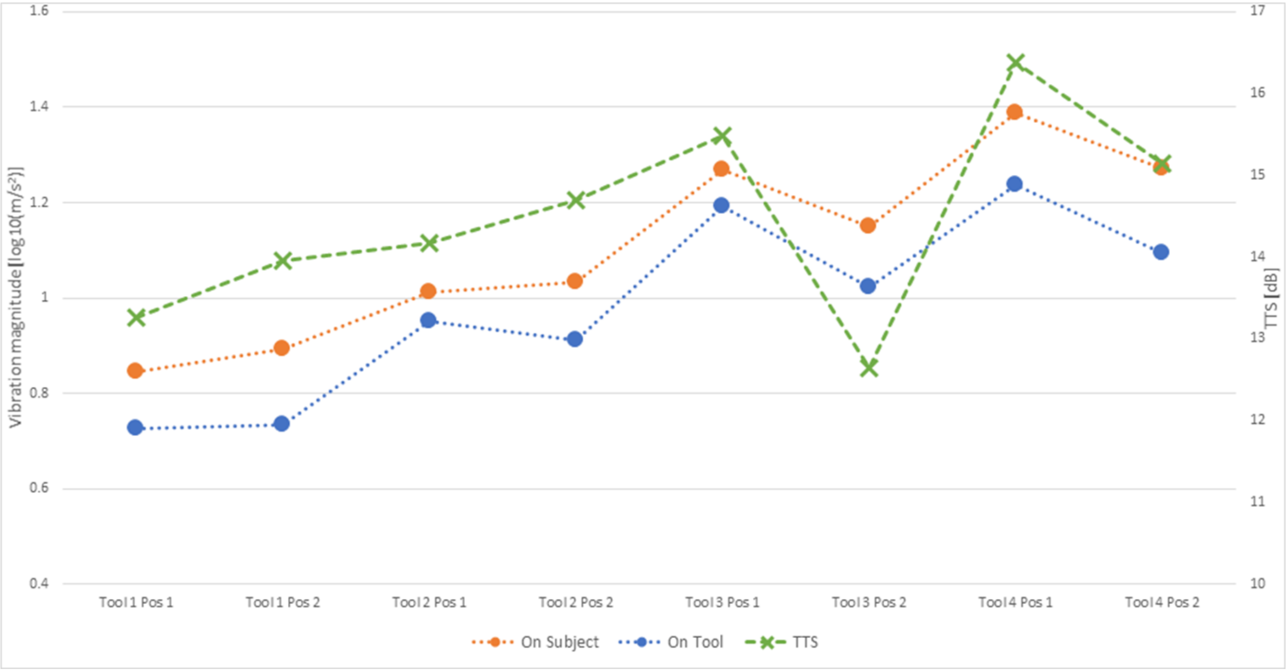

Figure 8: Mean TTS measurements (green) across the different test configurations, represented together with their respective vibration magnitude measurements, obtained on the tool (blue) and on the subject (orange).

The figure illustrates how the trend in human response to vibration are accurately predicted by both vibration magnitude measurements. The overall pattern is represented by a high coefficient of determination between TTS and vibration magnitude, with 0.70 for on-tool measurements and 0.71

for on-subject measurements. It must be noted that tool 3 was exceptionally challenging to handle for the operators in a horizontal position (posture 2), due to its weight distribution. If this result (Posture 2 in Tool 3) was removed from the analysis, the coefficients of determination rise to 0.94 and 0.96, respectively. This result confirms the effectiveness of both vibration measurement technologies for the assessment of potential risk for the operator.

The observed posture effects, both in terms of vibration magnitude and TTS for each pair of postures, are similar in terms of TTS and vibration magnitude. An exception can be found in tool 2, in which the transition from a downward to a horizontal position translates into an increase in vibration exposure, as measured by TTS. While measurements on the subject accurately capture this effect, the vibration measurements on the tool would have indicated the opposite trend.

5 CONCLUSION

The presented study offers a deeper insight into the effects of body posture on the vibration exposure of power tool operators in a typical civil engineering environment and illustrates the relative significance of certain factors listed within Annex D of ISO 5349-1 which are not typically captured in risk assessments. Correlation between the relative changes in assessed vibration and human response in each posture demonstrates that the change to assessed vibration is not merely an artefact arising from the different posture but does in fact have consequences for the risk faced by the individual.

As data from the study demonstrated, effects of posture change are not uniform across tools or posture. This is considered highly significant in the context of the current approach to managing risk from vibration in the workplace as these findings challenge the idea of a robust risk assessment using a formula of a fixed vibration magnitude and exposure time. The study highlighted that posture could affect the estimated safe time of working for the heavier tools by a factor of two.

A more detailed analysis of the relationship between findings from this study and the physiology of specific subjects would also be beneficial as the authors recognise the link between physiology and the ability to maintain certain postures more or less easily for certain subjects.

The ability of the modern wearable device to directly track vibration exposure transmitted to the operator in real time and its positive correlation with human response offers a promising avenue for improvement whereby risk might be managed on an individual level or at least risk assessments more widely informed through a more extended period of data gathering and from a wider cohort of operators. While the study has also demonstrated the ability of the current on tool methodology for vibration assessment to capture some of these effects the authors feel it is import to recognise that this form of measurement is rarely performed in the real worksite for both practical and economic reasons.

Further research will be necessary to characterise the effects of the other factors present in the real work environment, with the final aim of creating a model capable of offering an assessment of HAVS risk with the maximum accuracy.

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