Investigating the utility of wrist worn vibration monitoring in the effective management of exposure to dangerous vibrations within the work place

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Abstract

This paper seeks to demonstrate the validity of vibration data acquired from a personal wrist worn vibration monitor in assessing exposure to hazardous Hand Arm Vibration. The paper also seeks to define the value that data from continuous monitoring can have in forming an effective risk management process within the work place. Illustrated within this paper are some of the shortcomings arising from over reliance on single point sample measurements and the deviation between the perceived exposure calculated from a single point measurement and the reality of true exposure given the variability across time, task and a large cohort of individuals.

Introduction

Since Hand Arm Vibration Syndrome (HAVS) became a recognised medical condition, extensive scientific evidence has been published correlating exposure to vibration in the work place through use of mechanised tools with the development of the condition (1, 9, 10). In light of this evidence, legislation has been passed on a European level (2) and adopted across all 27 member states including the UK (3) to govern the levels of acceptable exposure and provide guidance on how to assess this within the work place. It should also be noted that the HSE state "Despite on-going research in the area of HAVS, quantitative exposure-response relationships for HAVS remain elusive and ill-defined. It has still not been possible to establish if there is a <u>no effect level</u> for vibration exposure, other than the somewhat obvious zero exposure level" (4).

In addition to this guidance, international standards (5, 6) were developed to formalise the process of measuring tool vibration which is of a nature that could lead to HAVS. While these standards explicitly state that large variances in work operation, tool condition and operator proficiency are likely to exist and there for should be included in a thorough risk assessment. In practice it is almost impossible to capture the full range of factors and combinations that effect exposure arising from any specific tool within the time frame normally allocated to such measurement activities.

Beyond the practicalities of actually taking measurements, further epidemiological studies into operator grip force have called into question whether a single weighting curve applied to measurements taken on the tool can accurately predict the dose transmitted to the operator (7). Therefore, this paper aims to investigate how the use of wrist worn continuous monitoring might be used to augment existing risk assessments and aid in the process of designing out vibration exposure through detailed analysis of exposure root cause and trends.

Problem Definition

Vibration generated from powered hand tools is intrinsically a highly variable mechanical property and therefor any assessment of this property will increase in accuracy the greater the duration of measurement and cohort size. Conversely, short duration tests taken in isolation are prone to being skewed by peaks or troughs incurred during the test which may not be indicative of typical vibration levels (5).

Beyond the intrinsic variability of vibration itself, the way vibration is generated from the use of power tools is highly task and operator dependant. While it may be possible to partially assess task dependant variability in some industries with highly repetitive operations such as manufacturing, in sectors such as construction it is almost impossible to fully capture the range of exposure conditions and operator proficiency at play across an organisation.

The waterfall plot in figure 1 illustrates the change in emitted vibration characteristics from a single high speed grinding tool being used in three different configurations (table 1) over a period of one minute. From the diagram it can be seen that in addition to a change in magnitude which might be expected from different operating configurations there is also significant changes in the frequency and dominant axis of the emitted vibration.

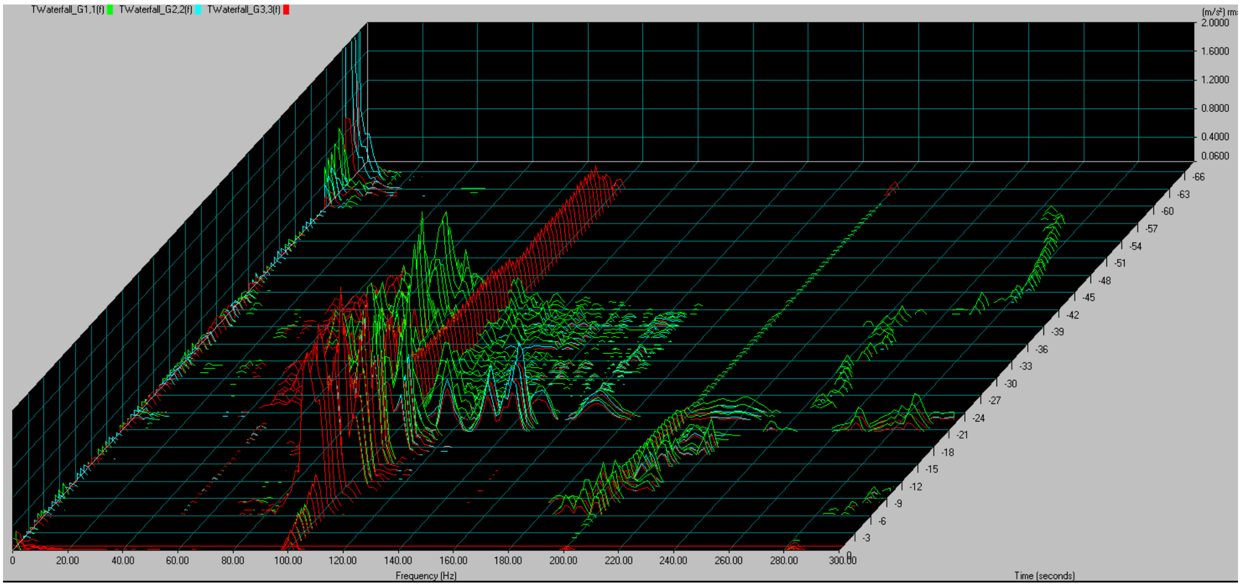

Figure 1 – Waterfall analysis of emitted vibration from single tool performing different operations

This visualisation of variability in emitted vibrations from a single tool, fitted with a specific consumable on a single material helps to illustrate that even in highly controlled environments, the use of a single value to determine vibration exposure across all use is unlikely to be representative of the true exposure.

Time Frame (seconds)	Test configuration	Points / hour
0 - 20	Light grinding aluminium	50
21 – 40	Heavy grinding aluminium	72
41 - 60	Free running in air	8

Table 1

For these reasons there is an opportunity to improve on the status quo by providing a monitoring solution that does not rely purely on assumptions or estimations and can also track changes in behaviour, task and tool wear.

Method

Before assessing the utility of data gathered from a wrist worn vibration monitor and how it might be used it is desirable to first validate the accuracy of the vibration exposure data against data acquired in compliance with the international standard ISO 5349. This validation will examine the ability of the wrist worn device to accurately capture vibration data in the frequency domain as well as the correlation of calculated overall dose from a wrist worn monitor versus that calculated in compliance with the international standard.

To assess the ability of the wrist worn device to accurately measure vibration frequency data, a series of measurements were taken concurrently using a wrist worn device (REACTEC HAVwear) and a reference instrument (Bruel & Kjaer Photon +) configured in accordance with ISO 8041 and used in line with ISO 5349 measurement practices. Test conditions required that a series of eight, single minute tests were undertaken using a Milwaukee M28 impact drill into concrete slabs. The graph in figure 2 illustrates extremely close correlation of vibration measurements taken using the two devices in the frequency domain.

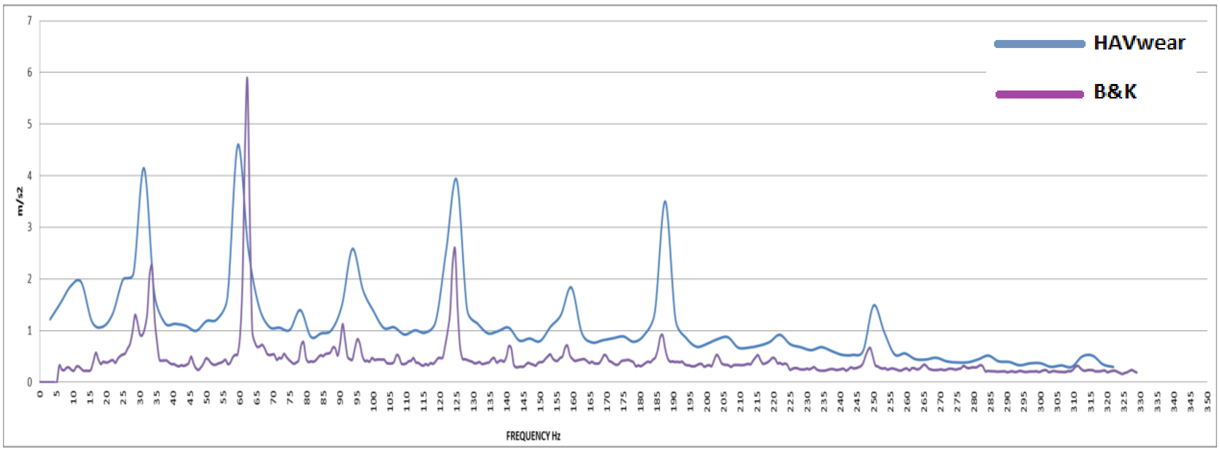

Figure 2 – Frequency domain analysis of vibration data captured by wrist worn monitor

Accurate correlation in the frequency domain is essential for hand arm vibration exposure assessment to ensure the overall dose is calculated correctly against the frequency weighting curve defined in ISO 5349 and that vibration generated at frequencies within the spectra of interest are transmitted through the wrist without being over or under attenuated. For the Bruel & Kjaer data illustrated in figure 2 the frequency weighting curve has been applied post capture.

The extremely close correlation within the frequency domain lends credence to the validity of measuring vibration on the wrist as an effective way of assessing exposure to harmful vibration.

To assess the ability of a wrist worn device to accurately assess overall exposure, a series of measurements were taken using the HAVwear device and two ISO 8041:2005 reference instruments attached to the tool handle in accordance with ISO 5349. In addition to the Bruel & Kjaer instrument a Svantek 106 instrument was used to illustrate that variability is present even within the use of ISO 8041

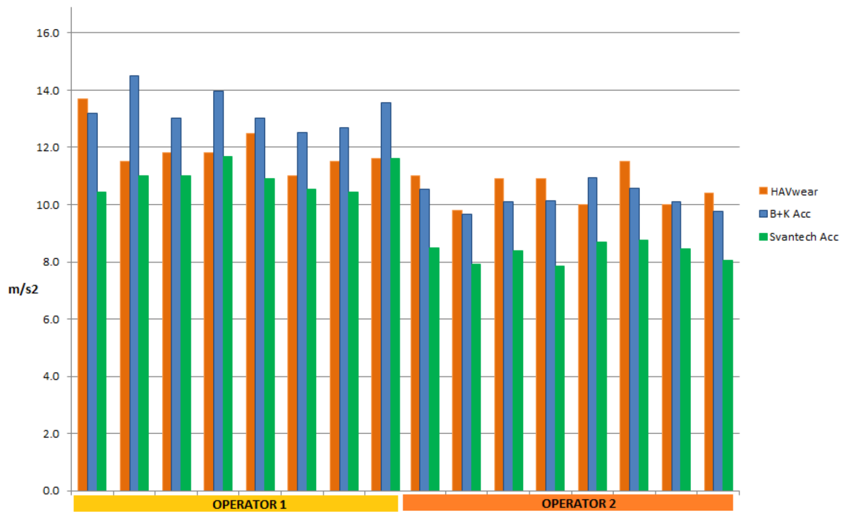

Figure 3 - Vibration magnitude correlation of wrist worn monitor

reference equipment. Figure 3 shows the test results conducted by two operators using a Milwaukee M28 impact drill into concrete slabs over a series of eight, one minute tests. While there is a degree of variability within each operators group of eight tests from all three devices, there is extremely strong correlation between the results from the wrist worn device and those from the two reference instruments. There is also a clear difference in the exposure dose between the two operators visible in table 2 illustrating the effect that different levels of operator proficiency has on the overall exposure.

Average exposure (m/s^2)	Operator 1	Operator 2
HAVwear	11.9	10.6
Bruel & kjaer	13.3	10.2
Svantek 106	11.0	8.3

Table 2

These results indicate that measurements taken on the wrist can provide an accurate representation of vibration exposure in simple lab test environment. However to prove that such a device is suitable to conduct this function in the field for the purposes of HAV exposure management requires validation against a much greater cohort of tools, operators and environments. The data gathered during this wider field validation will also help to illustrate the variability in exposure experienced even when performing the exact same operation multiple times for the purposes of validation.

To facilitate a more representative field test a major contractor was asked to assist in the validation exercise by providing a wide range of tools, trained operators and access to their active work site to permit validation of the wrist worn device in a real world environment. For these tests a Larson Davis HVM100 was the primary reference instrument with a Bruel & Kjaer Photon instrument used periodically to maintain reference measurements.

Thirteen tools were made available by the contractor at their London Bridge site to allow assessment of tool vibration performance utilising the Larson Davis and Bruel & Kjaer whilst wearing a HAVwear monitor. All data was recorded simultaneously during tool use in a real-world environment and was not available for comparison until testing was completed as data had to be logged in various data recording software off site. The benefit of this approach was there could be no attempts to affect recordings during the evaluations. In total 359 tool measurements were taken, with measurements repeated typically 30 times for each tool. Unless a measurement was interrupted by an event such as a tool breakage, a Larson Davis result was recorded for each HAVwear monitor reading, whilst a Bruel & Kjaer measurement was taken typically four times for each tool evaluation.

Figures 4 & 5 show results from tool measurements taken from the same two tools repeated up to 30 times and illustrate the high degree of variability in exposure present within a single tool during a single operation.

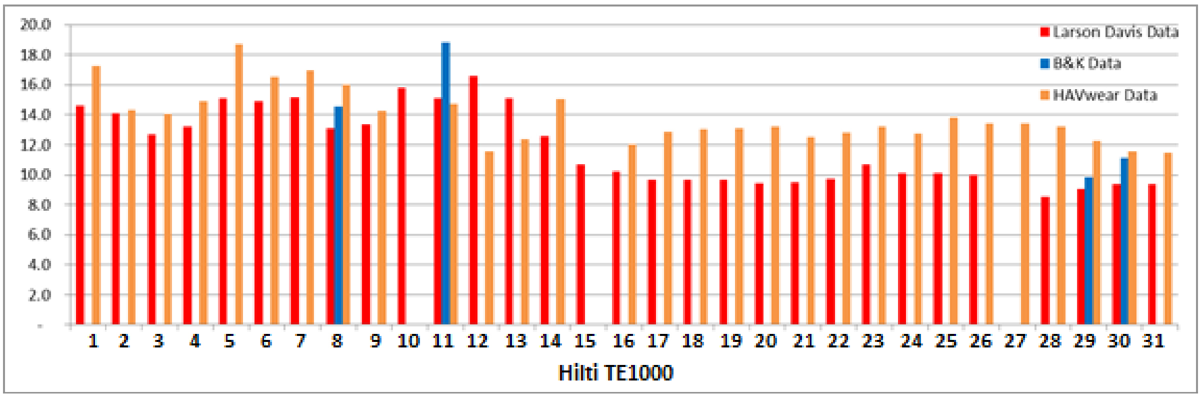

Figure 4 – Variability in vibration magnitudes within a single tool during a single operation

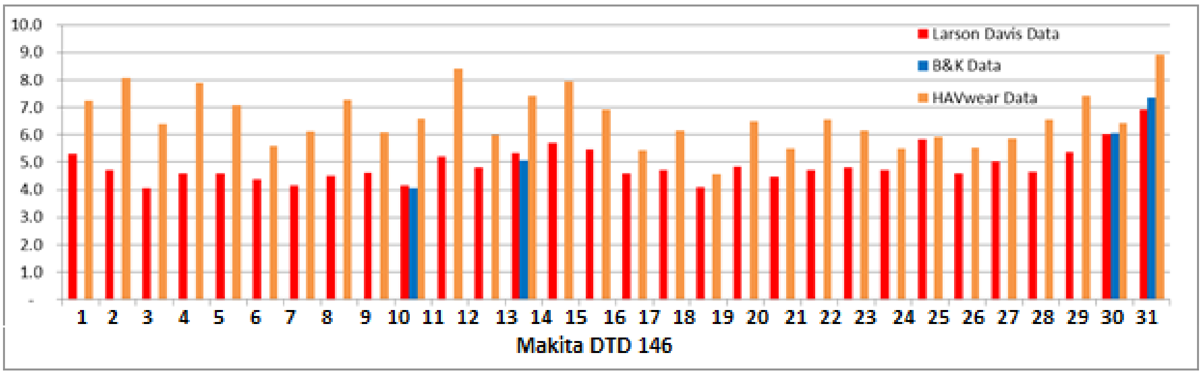

Figure 5 – Variability in vibration magnitudes within a single tool during a single operation

The data from figures 4 & 5 help to illustrate the merit of any form of continuous monitoring as it can been seen that vibration exposures can vary up to 50% on the same tool, performing the same task. When this is coupled with additional variables such operator proficiency, tool wear and different substrates this variance can be significantly higher still. While the HAVwear device is typically recording slightly higher than the reference instrument, there is very close correlation in the trend of the graphs.

				Larsen Davis				B&K				HAVwear				Variance		
Tool ID	Tool Description	Test Subst	Manufacturer data	Max	Min	Av	Count	Max	Min	Av	Count	Max	Min	Av	Count	B&K Variance to LD	HAVwear Variance to LD	HAVwear Variance to B&K
SK12 (T)	Demolition Hammer	Concrete	6.0	28.4	12.1	21.1	12	29.1	14.1	22.1	4	22.7	12.9	19.6	12	4%	-7%	-11%
Hilti TE1000 (T)	Breaker	Concrete	5.0	16.6	8.5	11.9	30	18.8	9.8	13.6	4	18.7	11.4	13.8	29	14%	16%	2%
Makita DTD 146 (T)	Impact Wrench	Timber	15.5	6.9	4.1	4.9	30	7.4	4.0	5.6	4	8.9	4.6	6.6	30	15%	35%	17%
Milwuakee 28 G2013 (T)	Cordless Drill	Timber	2.5	8.6	2.4	5.1	31	8.9	6.1	7.5	5	11.3	2.4	7.1	29	47%	39%	-6%
Makita Jigsaw 350CT (T)	Jigsaw	Timber	7.5	2.5	2.1	2.3	26	5.9	5.3	5.5	4	11.1	8.1	9.5	27	142%	318%	72%
Makita HR2610 (NST) 8mm short bit	Impact Drill	Concrete	15.5	8.2	6.1	7.0	4	15.9	15.9	15.9	1	17.7	12.1	16.2	4	126%	131%	2%
Makita HR2610 (T) 8mm long bit - sho	Impact Drill	Concrete	15.5	30.4	17.2	23.1	27	27.3	20.2	23.8	5	15.6	7.2	11.6	27	3%	-50%	-51%
Makita Reciprocating Saw REC275 (N	Reciprocating Saw	Timber	12.8	13.5	5.7	10.4	29	13.8	6.3	9.9	4	12.2	5.8	9.2	29	-5%	-11%	-6%
Metabo 5" Grinder T	Mains Grinder	Timber	7.0	22.4	8.1	12.7	32	18.4	7.2	12.2	5	10.5	4.8	7.7	29	-4%	-39%	-37%
Makita SDS DHR202 6mm long bit NS	Battery Impact Drill	Concrete	14.5	17.1	5.9	12.5	32	12.3	8.9	10.9	5	16.8	8.2	12.1	34	-12%	-3%	11%
Makita Paddle Mixer T	Paddle Mixer	Water	1.0	2.2	1.1	1.7	31	2.4	1.2	1.7	3	2.6	0.8	1.7	15	-4%	-4%	0%
Makita DHP456 (NST)	18V Cordless Drill	Timber	8.0	3.8	3.4	3.7	3	4.7	4.2	4.4	2	2.8	1.2	2.3	4	21%	-37%	-48%
Makita 5903R (NST)	Circular Saw	Timber	3.0	3.9	2.4	3.1	30	4.7	3.3		2	7.1	1.9	3.3	28		6%	
Makita JIG 121	Cordless Jigsaw	Timber	8.0	14.0	3.0	5.2	24	8.6	3.7	5.4	20	10.4	4.2	6.3	24	4%	21%	16%

Table 3

Table 3 summarises the overall variance of results averaged across all readings for the three devices. It is particularly worth noting the variability within the Max & Min data for the two ISO 8041 reference instruments. In general there is a very strong correlation between the Larson Davis measurement, the Bruel & Kjaer measurement and the HAVwear reading with the following exceptions:

- The Milwaukee G2013 cordless drill (timber substrate). During use the data determined by all 3 methods showed significant variation between each 1 minute trigger test. The HAVwear correlated well with the B&K, but was on average 39% higher than the Larson Davis
- The Makita 350CT Jigsaw (timber substrate) recorded inconsistent data across the three test methods. No conclusion can be drawn.
- The Makita HR2610 Impact Drill (concrete substrate). Testing of this tool was interrupted by a broken drill bit. Initial testing provided low vibration results from the Larson Davis while the B&K and HAVwear recorded data in line with manufacturer's data.
- The Metabo Angle grinder, a tool which is normally used to cut concrete or steel or to polish metal was used with timber as a hot certificate was not available at the time of testing. The physical size of the grinder is such that the Larson Davis and B&K accelerometers could not be mounted on the tool grip. The accelerometers were mounted on the top casing of the tool. The HAVwear would not therefore be expected to correlate with the other instruments.

The graph in figure 6 shows the average vibration magnitudes recorded by the three devices for each tool across the 30 or so repeat tests. Also plotted on figure 6 is the manufactures quoted data which has little or no correlation with many of the actual readings.

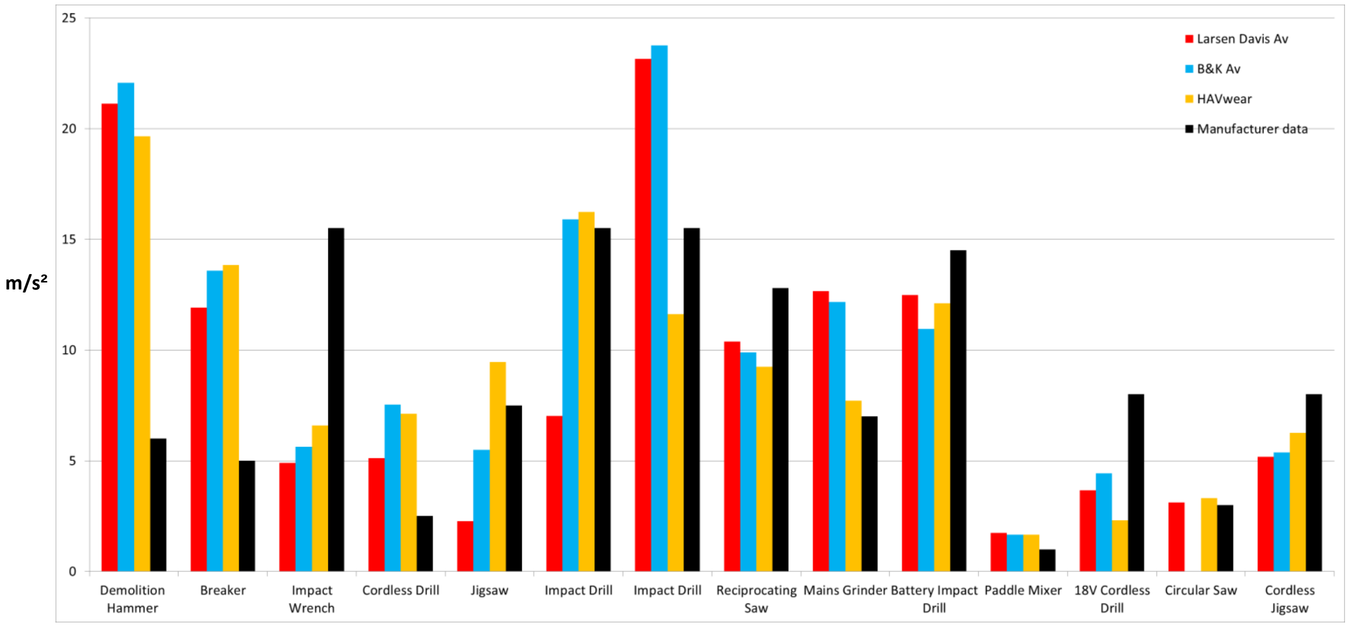

Figure 6 – Correlation between ISO compliant reference instrumentation and wrist worn monitor

The data clearly shows the correlation between data gathered on the wrist and data acquired in compliance with ISO 5349 using ISO 8041:2005 compliant equipment and therefor this data can be useful in making informed decisions on HAVs management processes within a business. For those concerned that the on wrist sensing of vibration exposure is not compliant with ISO 5349 it is worth noting that the wrist worn device is capable of operating in two modes one of which simply uses pre-programmed data multiplied by the sensed trigger time which allows the device to operate in full compliance with ISO 5349.

This compliant mode taken in conjunction with the sensed data provides users with the reassurance of a fully compliant solution while being able to take advantage of the latest sensory technology to guide their decision making.

Merits of continuous monitoring

As the validity of the wrist worn data has been established it is now desirable to fully understand the additional benefits this data offers the user as well as looking at the underlying benefits of continuous monitoring. Within the validation data it is clear to see the variability present when conducting the same operation using the same tool however this paper will now outline some of the main sources of variability across different tasks and operations to underline the shortcomings in a single point tool or task assessment.

It has been found that there is no typical working environment across many industries including manufacturing as tool use fluctuates from day to day and month to month. A risk assessment will be required to take this into consideration but will be open to error when relying on sampled data as the resulting average exposure estimation is based on a limited timeframe which can never hope to capture all conceivable fluctuations in activity and behavior present within a real world environment. Continuous monitoring reduces the margin of error associated with this estimation.

Figure 7 illustrates the variability of work activity over a six month period and highlights how an assessment conducted in February or late June would significantly underestimate operator exposure levels within the organization. This data was recorded at a manufacturing organization, a sector renowned for the use of time and motion studies to minimize variability in manual tasks.

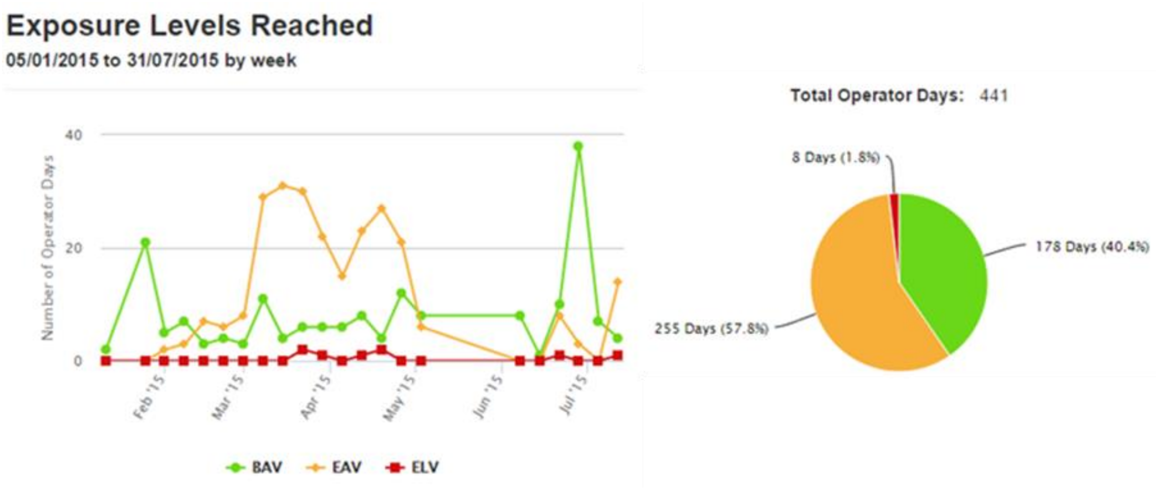

Figure 7 – Variability in daily exposure over time within a manufacturing organisation

The HSE acknowledges the existence of variability within real world application and advises the use of caution (3) when selecting vibration data for extrapolated exposure calculations to ensure it is truly representative of the actual exposure. Given the almost infinite number of variables which can contribute to a deviation from predefined exposure values it is unlikely that a sampling approach could ever cover all eventualities and therefor the only safe approach when taking sample measurements is to include a substantial K factor.

Applying a suitably large K factor should keep operators safe from over exposure assuming time keeping is accurate, however employers run the risk of reduced productivity if the actual vibration exposure is in reality considerably lower.

Beyond task and project based variance, it is widely accepted that significant differences in vibration magnitude can arise from different levels of operator proficiency. The graph in figure 8 illustrates the effect of operator proficiency on vibration exposure within a laboratory test environment. This data was collected as part of a witnessed test during which a series of continuous ten minute tests were conducted with two operators using the same drill into concrete. Operator A, a trained and experienced individual received a consistent transmitted dosage which closely matched the vibration measured on the tool using the ISO5349 reference instrument while operator B, a novice received a higher and more variable transmitted dose.

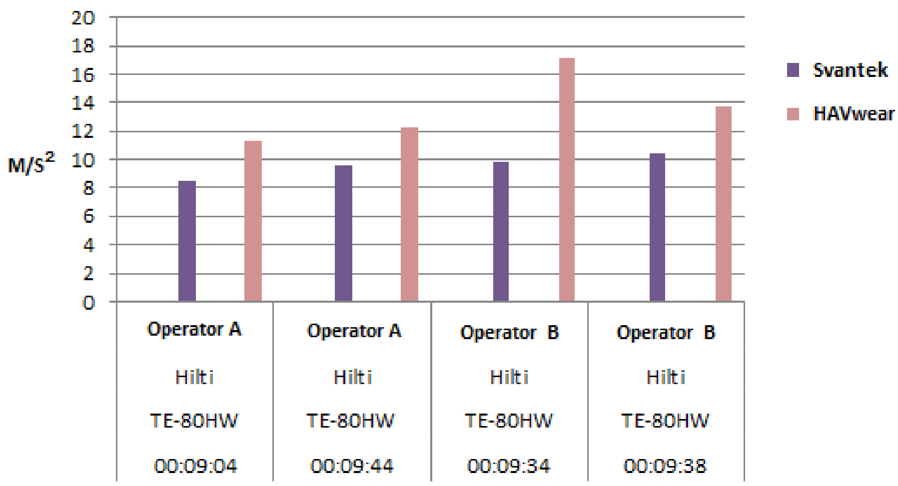

Figure 8 – Operator proficiency versus emitted vibration

This effect is magnified when seen outside the laboratory environment and Figures 9, 10 & 11 illustrate the variance in average vibration magnitudes across operators using the same tool over an extended period of time. The pre-programmed vibration magnitude for each tool is shown in blue whereas the average sensed vibration detected on the wrist is shown in red. Over extended use (table 4) it can be seen that actual transmitted vibration varies significantly across operators and as vibration exposure increases with the square of vibration magnitude the actual received dose varies even more significantly as illustrated in figures 12, 13 & 14.

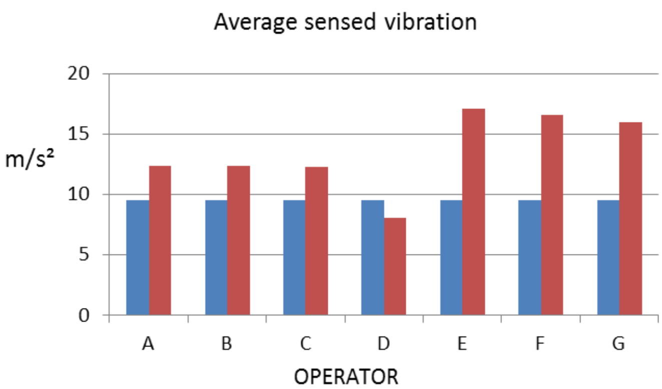

Figure 9

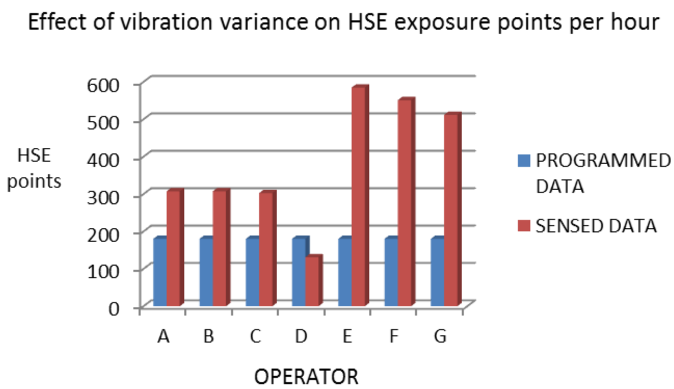

Figure 12

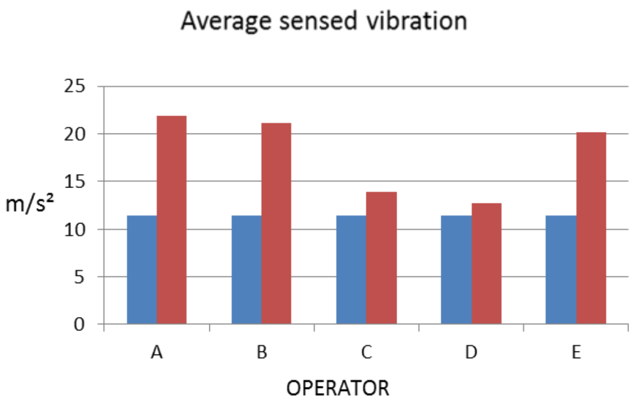

Figure 10

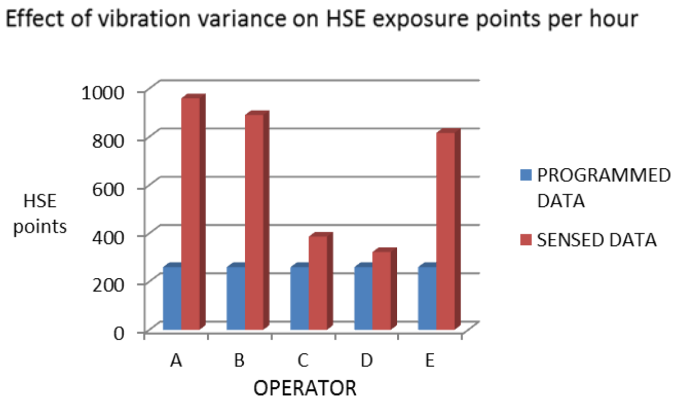

Figure 13

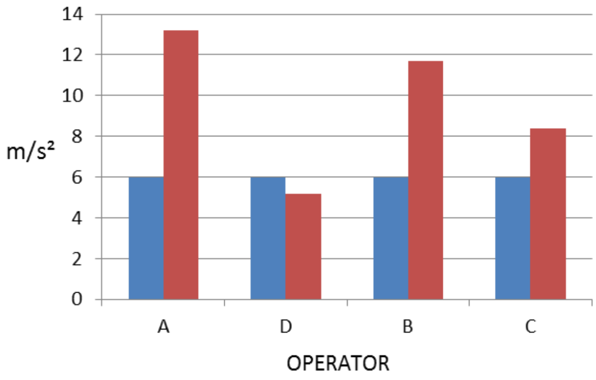

Figure 11

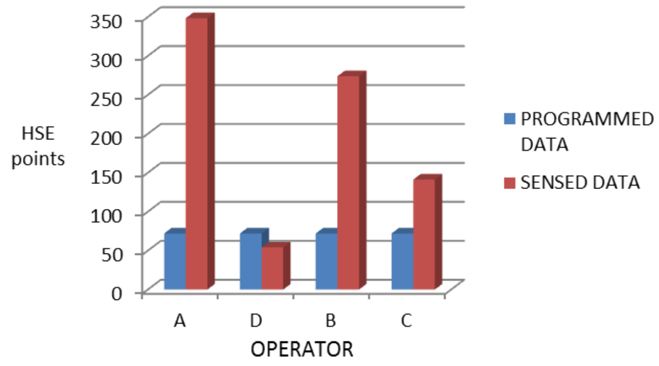

Figure 14

Figure	Tool	Operator	Trigger Time	Sensed vibration	Points per hour
X	Milwaukee 750 S	A	00:08:29	12.4	308
		B	00:56:34	12.4	308
		C	00:22:32	12.3	303
		D	00:16:48	8.1	131
		E	00:21:42	17.1	585
		F	00:24:41	16.6	551
		G	01:00:02	16.0	512
Y	Hilti TE50 AVR	A	00:49:15	21.9	959
		B	00:22:16	21.1	890
		C	02:08:39	13.9	386
		D	00:45:37	12.7	323
		E	00:21:18	20.2	816
Z	Bosch GWS12	A	01:15:03	13.2	348
		D	00:48:11	5.2	54
		B	02:21:51	11.7	274
		C	03:28:02	8.4	141

Table 4

Data analytics & business impact

Beyond ensuring exposure is kept within working limits in the short term, the ability to have real time continuous monitoring data which is traceable to tools, tasks and operator can aid significantly in the process of designing out exposure through identifying the source. Targeted procurement, process optimisation, improved tool maintenance and operator training are enabled through access to this data and can lead to significant reduction in exposure. The very nature of a wearable device that provides real time feedback to the operator can also facilitate behavioural change and a level of awareness that are not possible through periodic interventions.

The Control of Vibration at Work Regulations of 2005 stipulates that simply keeping exposure below the action and limit values is not sufficient (3). To ensure compliance, employers must reduce exposure levels to lowest practicable levels. The process of reducing exposure and also providing evidence of this is greatly aided with the advent of real time exposure monitoring and associated analytical tools. Figure 15 illustrates the progress made by a major global construction organisation in reducing exposure to hazardous hand arm vibrations through the use of real time monitory and illustrates how leveraging the power of analytical data to drive decision making within the organisation can have significant and measureable impact.

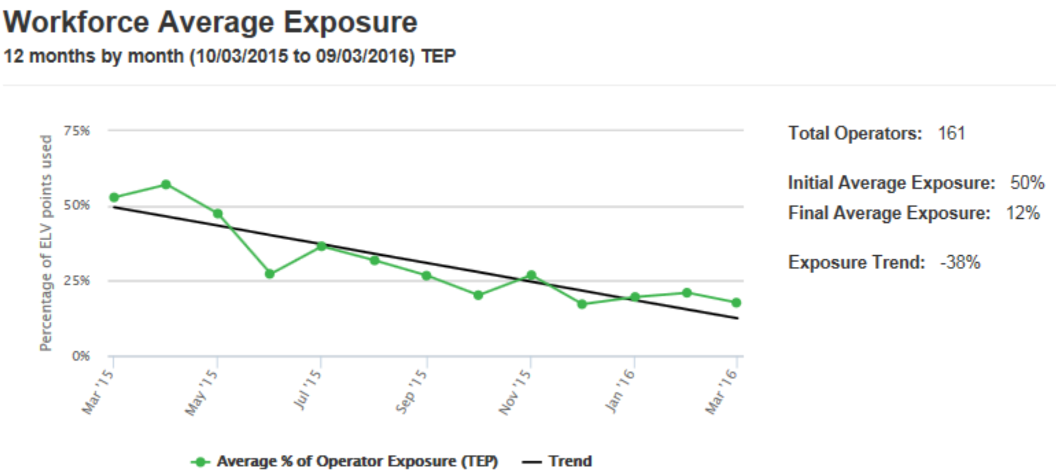

Figure 15 – Progress made by a major construction organisation in reducing operator exposure

Looking beyond HAVs, the value of continuous monitoring of business or industrial processes and the analysis of this data for decision making purposes is now widely recognised. KEYSTONE Strategy recently published a white paper which examines how enterprises performing in the top 25% of their peer group are significantly more likely to leverage real time data monitoring and analytics across their organisation (8). The paper found that companies utilising these capabilities as part of regular business practice across their organisation enjoy operating margins that are eight percentage points higher than organisations lagging in the deployment of such tools.

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