Advances in Intelligent Systems and Computing 973

Tareq Ahram *Editor*

Advances in Human Factors in Wearable Technologies and Game Design

Proceedings of the AHFE 2019 International Conference on Human Factors and Wearable Technologies, and the AHFE International Conference on Game Design and Virtual Environments, July 24–28, 2019, Washington D.C., USA

Springer

Current Situation and Problems of Hand-Transmitted Vibration Measurement and Monitoring Equipment and Benefits of Wearable Sensors for Everyday Monitoring

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Abstract. Employers who expose their workforce to hazardous vibration from mechanized tools need to develop an understanding of the health risk their employees face as a consequence. ISO 5349-2 was developed as an international standard to define how vibration exposure should be measured to quantify the risk to the individual. The authors would contend that the standard does not facilitate the economic collection of data across a range of tool users on a routine basis. In this paper, the Current Situation of Monitoring equipment for Hand-Transmitted Vibration Measurement is summarized with a review of the equipment's functionality. The paper then examines evidence from a time in motion study of a group of skilled operators repeatedly performing a single task to highlight the broad variability in monitored exposure levels relative to that expected. The authors conclude with the benefits the wearable sensor offers as a practical everyday assessment relative to existing methodologies.

Keywords: Wearable sensor · Hand-transmitted vibration · HAVS · ISO 5349 · Regular monitoring · Exposure data analytics

1 Introduction

From the increasing number of exhibitions on wearable technologies including the Wearable EXPO in Tokyo, Japan on January 2019 and as published in the conference proceedings of AHFE2018 [1], wearable sensor technology developed for the purposes of health monitoring can be distinguished into two categories. The first category focuses on measuring parameters or vital signs from the human body as indicated on the right-hand side of Fig. 1. The second category, as illustrated on the left of Fig. 1, is focused on the detection of risks to the human body for the purpose of damage prevention to the body.

T. Ahram (Ed.): AHFE 2019, AISC 973, pp. 82–92, 2020.
https://doi.org/10.1007/978-3-030-20476-1_10

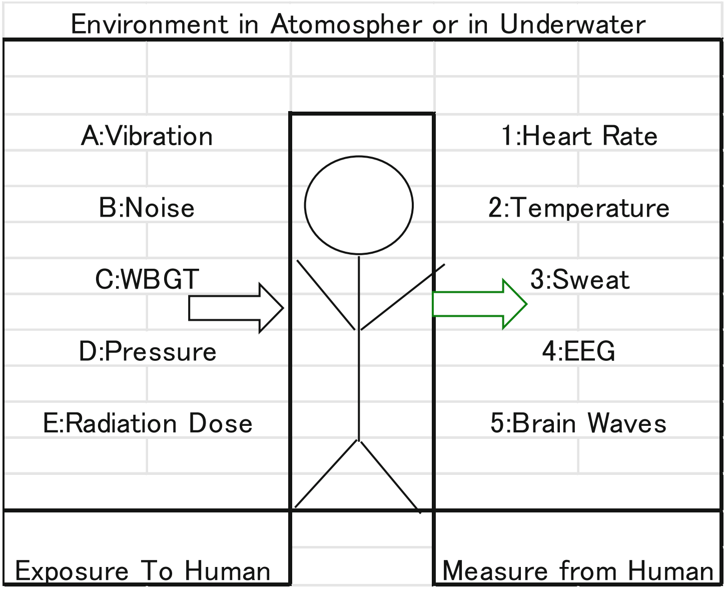

Fig. 1. Current wearable sensor technology.

The right-hand side of Fig. 1 concerns condition monitoring of the individual by sensing data measured from the human body, such as heart rate, body temperature, etc. From No.1 to No.5, the wearable equipment is measuring the effect on human body function in reaction to outside stimuli. Although these functional effects can be monitored using the wearable device, the underlying stimulus or physical agent is not monitored and therefore it is difficult to reduce or prevent adverse effects.

The left-hand side of Fig. 1 is focused on the prevention of risk to the human in the workplace by measuring the physical agents present in the environment such as A (Whole-Body Vibration and Hand-Arm Vibration measurement equipment: ISO 8041), B (Noise Dose measurement equipment: ISO 9612), C (Wet-bulb globe temperature measurement equipment: ISO 7243, 8996, 7726), D (Dive Computer: ISO 6425), and E (Radiological Protection: ISO 16637, 17025, 27048). All such wearable instruments have been measuring various physical quantities indirectly exposed to the human body in the work environment.

Exposure to vibration through the hand and arm system, known as Hand Arm Vibration (HAV), or through other areas of the body, known as Whole Body Vibration, are both known to cause irreversible damage. Exposure to HAV can cause neurological, vascular and musculoskeletal damage with the symptoms referred collectively as HAV Syndrome [2]. The established method for managing HAV exposure risk has been standardized in the form of ISO 5349 (BSI, 2001a), with employers being required to control exposure levels to predetermined limits of daily exposure within their respective territorial legislation. The standard also outlines the perceived probability of developing vascular damage from exposure to HAV based on an average daily exposure dose. Per ISO 5349, HAV risk is determined from the time duration of HAV exposure and a specific processing of the vibration magnitude during exposure. As will be expanded upon in Sect. 2, a range of instrumentation has been developed over time to quantify either one or both vibration exposure characteristics. Instrumentation aimed at fully complying with ISO 5349 requires the placement of accelerometers on the tool surface while in use and instrumentation of a nature which requires a skilled technician to interpret the gathered data. In essence, the standard does not facilitate the economic collection of data across a range of tool users on a routine basis, yet the accepted understanding of the likelihood of health damage is determined by average daily exposure levels requiring detailed data of regular daily activities. Despite the existence of the 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 [3]. This paper explores the ability of wearable technologies to readily collect large data sets and examines whether utilization of data acquired in this fashion might provide for a more effective risk assessment and furthermore act as a preventative measure to this disease by ensuring timely intervention.

2 Comparison of Current Hand-Arm Vibration Measurement Instruments

In 2013 Pitts and Kaulbars [4] examined the limitations of measurement and instrumentation standards relative to the emergence of instrumentation aimed at easing the gathering of personal HAV exposure data. In doing so the definitions of Table 1 were

Table 1. Key elements of systems used for assessing vibration magnitude, exposure time and daily vibration exposure.

Name	Definition
Machine operation timer	Device for measuring the time for which a machine is operating (e.g. based on power take up or machine vibration)
Personal vibration exposure timer	Device for measuring the time for which either a hand is in contact with a vibrating machine or the body is in contact with the seat (e.g. using a switch to detect contact times with the vibrating surface)
Human vibration indicator	Instrument that measures a vibration value but whose measurements cannot conform with ISO 5349 and/or ISO 2631 - due to, for example, the transducer position being away from the hand grip or away from the centre of the seat.
Human vibration meter	Instrument conforming to ISO 8041 for measuring vibration magnitudes in accordance with ISO 5349 and/or ISO 2631
Personal human vibration exposure meter (PVEM)	Instrument for measuring daily vibration exposures, based on a measurement that directly determines the vibration exposure of a worker.[a]

[a]No assumptions are made at this stage as to whether a PVEM fully meets the requirements of ISO instrumentation or vibration measurement standards. Such an instrument might, for example, make a measurement on the hand of an operator that has been shown to be (within acceptable tolerances) equivalent to a measurement in accordance with ISO 5349-1.

developed to clarify instrumentation capabilities. ISO/TC108/WG33 as a consequence is considering the hand-arm vibration standard, such as ISO/NWIP 8041-2 standard. The examination of Pitts and Kaulbars [4] predated the emergence of wearable device to determine directly on the tool user the vibration risk transmitted to the user.

Pitts and Kaulbars recognized that prior to 2005, when the instrumentation standard was developed, most instruments on the market where aimed at researchers or vibration specialists. While the research market may need precision and reliability of measurement, employers aiming to protect their workforce have a need for practical, routine monitoring of vibration exposure which is not consistent with these instruments. Despite acknowledging the need for ease of data collection, recognition of the standard drove most of the instrumentation reviewed by Pitts and Kaulbars to arrange that sensors come into direct contact with the tool handle or to compromise and measure only vibration exposure time. Unfortunately, vibration magnitude has a greater influence on risk of injury relative to time as the dose is calculated from the square of the magnitude [5] and vibration magnitude is known to be largely variable depending on the condition of the tool, the material being worked on, the quality of tool accessories and the skill of the worker. An instrument realizing all the functionality of a PVEM was therefore considered the most useful. A PVEM was also considered the most challenging to develop a standard for, due to the practical challenges of the mounting of the sensors on the tool grip point. Ironically, Annex D of the ISO 5349-1 standard identifies the limitations of measuring hand transmitted vibration on the tool handle principally due to the tool operator's influence on the level of vibration transmitted to him while he is in contact with the tool. Within clause 4.3 of this standard, it is stated that the characterization of the vibration exposure is assessed from the acceleration of the surface in contact with the hand as the primary quantity. Therefore, ISO 5349-1 [5] assumes that the hand-transmitted vibration exposure magnitude is the tool handle vibration measurement, while the reality is that the hand-transmitted vibration is affected by the many factors listed in Annex D of ISO 5349-1 standard as shown in Fig. 2.

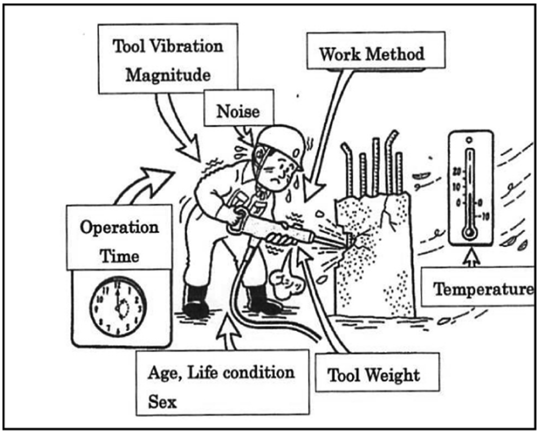

Fig. 2. Factors likely to influence the effects of human exposure the hand-transmitted vibration in the working conditions of Annex D of the ISO 5349-1 standard.

For many years, the factors outlined within Annex D of ISO 5349-1 have not been adequately captured when making an assessment of hand-transmitted vibration exposure for the purposes of prevention of HAVS in real world environments. A desire by employers to adhere strictly to the ISO 5349-1 standard may be contributing to inaccurate dose assessments and inferior outcomes for the worker. Wearable sensors mounted on the tool user offer the opportunity of determining the vibration transmitted to the user potentially offering a more credible answer to the need for practical everyday monitors.

3 New Consideration of Hand-Transmitted Vibration Measurement Wearable Sensor

Within this section the suitability of one wearable personal vibration exposure meter for use in the effective management and reduction of vibration exposure will be examined. Compliance with ISO 5349-1 & ISO 8041 is not claimed by the manufacturer and therefore this paper does not seek to demonstrate absolute equivalence, rather it merely seeks to demonstrate the relevance of data acquired from such a device in the effective management of risk. See Fig. 3.

The HAVwear system (Reactec Ltd) combines a number of emerging technologies to provide the user with real time vibration exposure data pertinent to their work activities via an LCD and audible warnings in addition to a suite of analytics tools to enable the design out of harmful vibration. A ruggedized wearable device for data acquisition is coupled with an IOT enabled docking station to upload vibration data to a cloud based analytics platform.

The wearable device mounts to an operators wrist by way of an adjustable nylon webbing strap and comprises a 3 – axis linear MEMS accelerometer sampling at 1.6 kHz for 0.66 s every 1.5 s. A frequency range from 3 Hz to 650 Hz is captured. Acceleration data from each axis is converted independently from time domain to frequency domain through a 1024 point Fourier analysis incorporating a Hanning window function to generate 512 discrete magnitude values for each axis. The corresponding frequency point magnitude values for each axis are then combined to create an overall magnitude value for each point on the spectrum. A proprietary transfer function is then applied to each value across the spectrum to calculate the instantaneous magnitude detected at the wrist. This transfer function compensates for attenuation of the biomechanical structures of the hand and is designed to provide parity with measurements taken on the tool in accordance with ISO 5349-1. Overall exposure is calculated by means of a rolling RMS for the duration of the trigger time. Parity with measurements taken in accordance with existing ISO standards is desirable for calculating exposure as all current research and knowledge on the pathogenesis and progression of the disease is based on exposure calculated to these standards.

The instrument's capabilities have been examined in two recent bodies of work. A UK independent research and consultancy services organization, the Institute of Occupational Medicine [6], carried out an extensive exercise to compare the vibration magnitude determined by the wearable sensor with that taken concurrently in full compliance to the standards over a broad range of tools. Maeda et al. [7] examined the strength of correlation of the wearable's vibration determination and the human response to vibration.

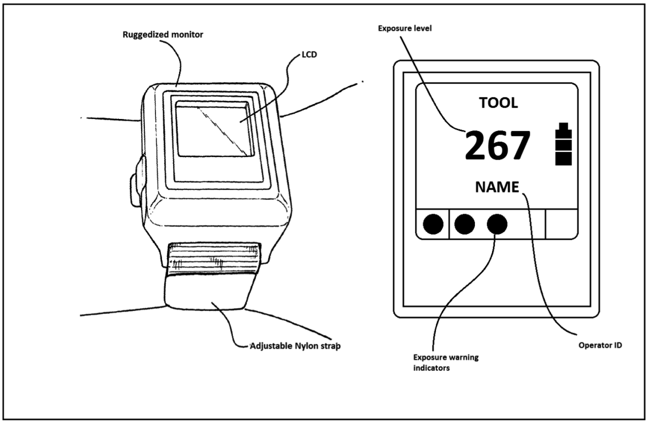

Fig. 3. Wearable Personal Vibration Exposure Meter (HVW-001, Reactec Ltd).

The true value of the wearable device comes from its ability to capture the variance in exposure and deviation from the anticipated risk. The traditional risk assessment approach of task based assessment relies on tool performance, substrate consistency, operator proficiency and vibrating tool work load allocation all remaining constant which in practice rarely happens. Additionally, 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 [8].

To illustrate the variability from tasks a detailed risk assessment exercise was carried out on the work of 14 tool operators in multimen teams, each excavating the same size hole within the same grade of road surface. Each operator used the same tool type for which the duty holder had determined a vibration magnitude of 12 m/s^2 through the use of extensive live testing in accordance with ISO 5349. Note this was well in excess of the tool vibration data declared by the manufacturer of 4.2 m/s^2. The duty holder had determined that, was inappropriate for the type of road surface under test. A mix of site teams were used per excavation which consisted of between two and four man operator teams.

Figure 4 displays the calculated total exposure risk in A(8) m/s^2 for/at each excavation broken down by the contribution to each excavation by each operator. Each team accomplished the same task within different time durations. The colors within each excavation show the relative contribution from each team member of each excavation. The wide range of exposures clearly illustrate the limitations of a static risk assessment, whereby even if the most extreme results are disregarded the exposure per excavation ranged ±40% on the mean value.

A task based assesment of these excavations would potentially determine the average exposure per excavation to be an A(8) of 4.2 m/s^2 and therefore if the work was evenly shared a two man team would be exposed to an A(8) of 2.9 m/s^2 and a three man team exposed to an A(8) of 2.4 m/s^2. A task based assessment will typically only account for an average exposure risk per task, not the actual exposure of individual operators.

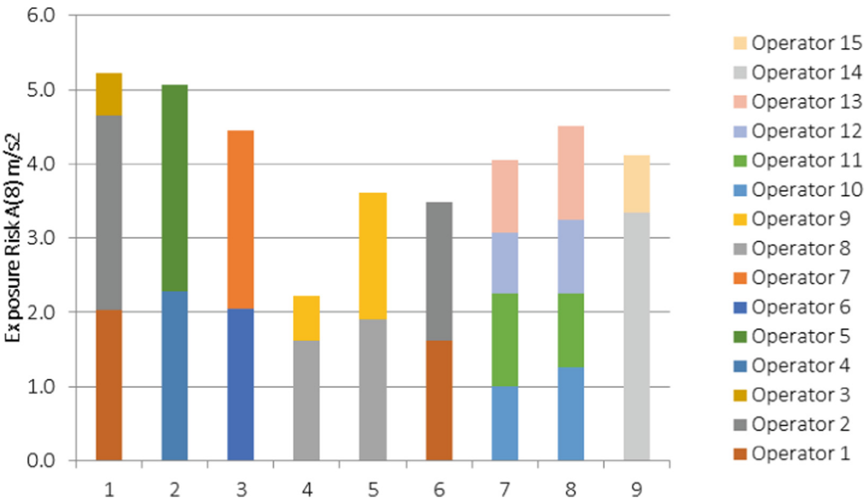

Fig. 4. Calculated total exposure in A(8) m/s^2 for each excavation

The assessment also included live tool vibration testing which took place during these excavations. Two methods were used to determine the vibration level.

1. An ISO5349-1 measurement using a reference instrument (HVM100, Larson Davis) operated by a skilled technician
2. Data collected using industrial wearable device (HVW-001, Reactec Ltd.) on a HAVwear worn by the tool operator.

The data from both is depicted in Fig. 5, which shows the numerical average of the RMS vibration level determined by the two devices. Strong correlation can be seen between the wearable sensor and the ISO5349 compliant reference instrument with an overall average for the reference instrument of 11.1 m/s2 and 11.9 m/s2 for the wearable device.

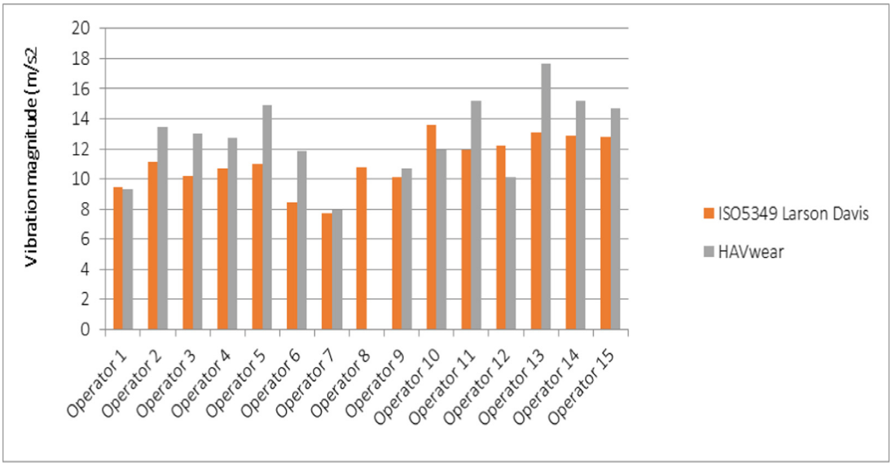

Fig. 5. The data from both companies, such as Larson Davis and HAVwear.

Figure 6 depicts the calculated maximum HAV exposure for each individual when excavating just one hole from the actual trigger time and real-time vibration data from the wearable device. Using a conventional task based assessment with a minimum two operator team the expected max risk would be an A(8) of 2.9 m/s^2. In reality, 5 out of the 14 operators exceeded this level. This data leads the investigators to conclude that job rotation is unlikely to be as expected without monitoring and furthermore each operator is unique in technique and physicality, which can lend itself to a high level of variability in exposure risk. Operator 5's exposure was close to the limit exposure level of 5 m/s^2 and 6 times that of some other operators tasked with the same duties. Given that there is no safe level and employers are required to reduce the exposure to as low as is reasonably practical it is clear in this case that the risk is being concentrated on certain individuals without their knowledge.

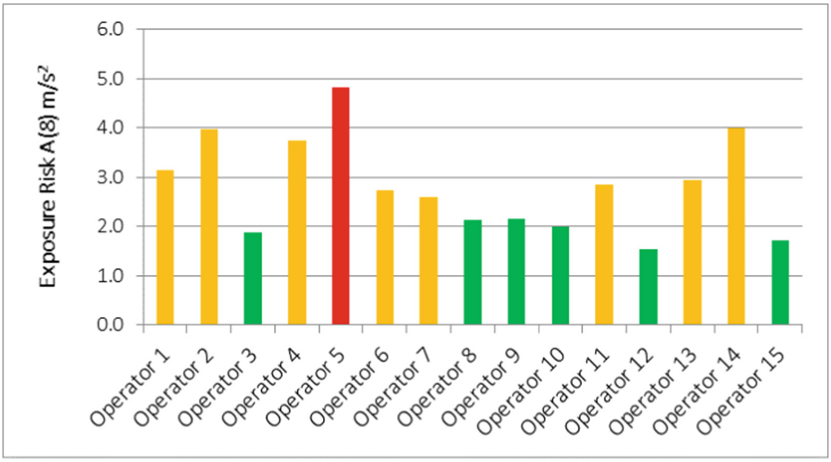

Fig. 6. Calculated maximum HAV risk exposure for each individual for one excavation

The UK Health and Safety Executive (HSE) acknowledges the existence of variability within real world application and advises the use of caution when selecting vibration data for extrapolated exposure calculations to ensure it is truly representative of the actual exposure [8].

Combining the wearable technology with IOT data transmission and cloud based analytics has for the first time allowed for the collection and review of truly "Big Data" regarding vibration exposure. Analysis of this data suggests that there is a significant delta between perceived exposure levels and actual exposure. The wearable system provides for data collection in two modes of operation. The first mode senses the true vibration transmitted to the tool operator and a second mode that calculates exposure from a pre-programed RFID tag attached to the tool in use. By analyzing data from heavily used tools we can plot the manufacturer's declared vibration level and the average assumed value used in risk assessments from the RFID tag against a histogram of actual vibration values recorded on the wearable device. Figures 7 and 8 illustrate the delta between the average vibration value used during risk assessments of one specific tool used and the histogram of actual vibration recorded by the wearable device over 2,850 h of trigger use of the tool. The X axis in Figs. 7 and 8 denotes the vibration magnitude in discrete ranges. The Y axis denotes the number of days in which individual operators experienced the level of vibration at each discrete range when using the tool.

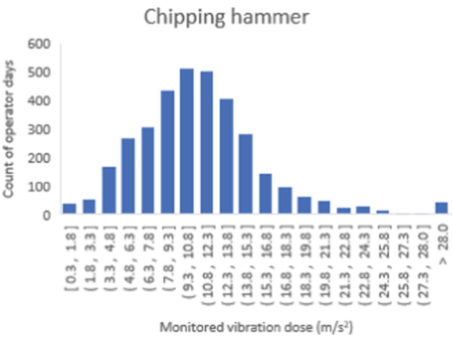

Fig. 7. Operator day instances of in-use monitored vibration magnitude – chipping hammer

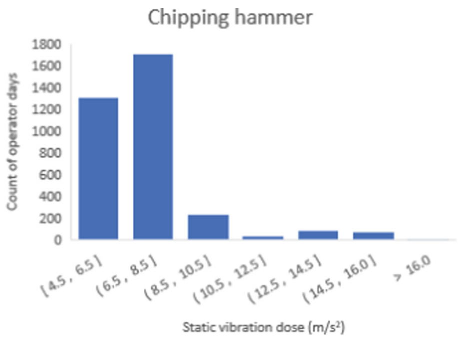

Fig. 8. Operator day instances of static vibration magnitude – chipping hammer

For the tool shown in Figs. 7 and 8, a separate tool testing exercise had been conducted on a live demolition site. A series of 30 X single minute duration trigger tests compliant to ISO5349 yielded an average vibration level of 11.9 m/s2 while a monitor worn during testing averaged 13.8 m/s2. Analysis of this large data set coupled with the field validation of the specific tool, lead the investigators to conclude that a significant delta must be present between the assumed static value used in the risk assessments of analysed organisations and the actual risk faced by many of their tool users.

Beyond ensuring exposure is kept within regulated limits in the short term, the ability to have real time continuous monitoring data which is traceable to tools, tasks and operators 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 facilitate behavioral changes and a level of awareness that are not possible through periodic interventions.

In UK legislation, the Control of Vibration at Work Regulations of 2005 stipulates that simply keeping exposure below the action and limit values is not sufficient [9]. 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 9 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 measurable impact. The Y axis of the graph denotes the exposure as a percentage of predefined exposure limit values for monitored operators utilizing the UK points based system.

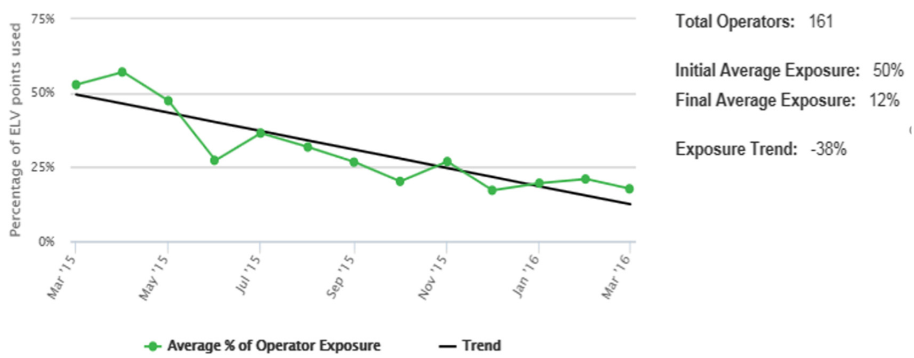

Fig. 9. Workforce average exposure within a major construction organisation following the introduction of wearable monitoring technology

4 Conclusions

The ISO 5349-1 AND the EU directive a relationship between health damage and the daily exposure to hand arm vibration. However, this standard and its emphasis of making measurements on the tool with instruments following ISO 8041-1 is recognized as suited to research environments, but not to regular employee risk monitoring. Given the wide range of emitted tool vibrations over a tools' normal course of use, it would seem logical that employers need access to practical everyday monitoring devices to prevent harm to their employees. The authors have presented data to highlight the variability that exists in every day tasks when examining closely a controlled assessment of work and the practical way in which a wearable devise can gather the necessary day that will affect an individual's direct health risk.

The authors believe there is an opportunity to more intelligently develop HAV exposure control measures with a more detailed insight to the drivers of HAV exposure risk than that developed from generic HAV risk assessments based on assumed static vibration dosages.

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