

Comparison of vibration measurement accuracy between a low cost, portable inertial  
measurement unit system and a gold-standard accelerometer system

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**Abstract**

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**Introduction:** Characterization of Whole-Body Vibration (WBV) exposure is important for the development and evaluation of mitigation strategies for occupational WBV. Traditional gold standard accelerometer (GSA) systems can be bulky, expensive, and difficult to implement in real world testing. Recently, relatively inexpensive, compact Inertial Measurement Unit (IMU) devices, which have built-in batteries and memory and are capable of collecting WBV exposure data, have emerged. While the ease of use of these devices may allow for more efficient collection of WBV exposure data, it must be determined if the data collected are comparable to data collected from traditional GSA systems.

**Methods:** Using an accelerometer calibrator, a GSA system and IMU device were used to measure known sinusoidal acceleration inputs of different frequencies (2, 8, 16, 32, 100 Hz) and amplitudes (0.125, 0.25, 0.50, 1.0, 5.0 m/s<sup>2</sup>). The errors of these measurements to the known values were compared, as well as the inter-tool agreement of the measurements of the systems. The measures under consideration were the unweighted root mean square acceleration (URMS) and weighted acceleration ( $A_{eq}$ ). Next, using a shaker table and single axis real-world, random vibration profile inputs collected from an SUV traversing a cobblestone road and a rough bumpy road, parallel measurements were performed with a GSA and IMU. The measures under consideration were the  $A_{eq}$  and vibration dose value (VDV). For both tests, a relative difference in measurements between the two systems of 10% or less was deemed to be an acceptable margin of error.

**Results:** In sinusoidal testing with the accelerometer calibrator, the grand mean unweighted error of the IMU device was -0.081 m/s<sup>2</sup> (-7.6%) and fell within the a priori range of acceptable error, with the largest errors occurring at 100 Hz. The grand mean weighted error of the IMU was less than the unweighted error, with a value of 0.006 m/s<sup>2</sup> (1.2%). Using Bland-Altman analysis, there was no statistically significant difference in measurements between the IMU device and GSA system with the unweighted measurements (mean difference 0.084 m/s<sup>2</sup>, p=0.19) or the weighted measurements (mean difference -0.001 m/s<sup>2</sup>, p=0.95). In the random vibration profile testing, the differences in weighted ( $A_{eq}$ ) measurements fell within acceptable ranges with an average difference of 0.06 m/s<sup>2</sup> (4.6%). Differences in VDV measurements were also within acceptable ranges with an average difference of 1.2 m/s<sup>1.75</sup> (4.1%).

**Discussion:** The IMU device was found to have comparable measurement accuracy to the GSA system in measuring sinusoidal inputs, with relative errors of less than 10% in both URMS and  $A_{eq}$  measurements, and no statistically significant difference in inter-tool agreement between the systems. In the random profile vibration testing, the weighted  $A_{eq}$  and VDV measurement differences between systems were both below the a priori 10% limits. As the weighted vibration values are used when assessing occupational exposures, these results suggest that the IMU device may be an acceptable replacement for GSA systems in measuring occupational vibration exposures.

## **Introduction:**

Whole body vibration (WBV) is the vibration transmitted to the body by the surface supporting it, most commonly from the seat or floor of the vehicle being operated.<sup>1</sup> WBV exposures are vector quantities characterized by the acceleration of the exposure, or how the motion of the vibration-exposed person changes and/or accumulates over time in terms of the magnitude and the frequency content of the exposure, typically in Hz.<sup>2</sup> Certain frequency domains are recognized as more impactful to human health, predominantly those between 4 and 12 Hz, primarily due to the resonant frequencies of the anatomical structures of the body.<sup>3</sup> These exposures are common amongst drivers and operators of vehicles and other machinery and can be augmented by several occupational factors including posture and workplace conditions.<sup>4,5,6</sup> WBV exposures are associated with numerous adverse health effects.<sup>7,8</sup> The most studied health outcome associated with WBV exposure is low back pain, with occupational studies showing up to 2.17 (95% CI:1.61 – 2.91) times the odds of subjective pain symptoms for the lower back in workers in jobs exposed to occupational WBV as compared to workers in jobs without significant WBV exposure.<sup>9,10</sup> Additionally, WBV exposure has been linked with a multitude of other potential health effects including stomach and digestive conditions, neurologic, cardiovascular, endocrine and metabolic disturbances, and reproductive organ damage, among others.<sup>1,4,7,8</sup> Studies of acute effects of occupational WBV exposures have also shown decreased performance of work tasks and other neurocognitive and physiologic effects.<sup>11,12,13</sup> In experimental studies, drivers exposed to high levels of WBV had increased low back pain and decreased vigilance and poorer driving as compared to drivers with mitigated WBV exposures.<sup>14</sup> Drivers scored significantly poorer on a battery of tests evaluating neurologic, vestibular, and cognitive domains after experiencing WBV exposures, as compared to prior to their exposure.<sup>15</sup> However due to barriers in the consistent

measurement of WBV exposures, adequate epidemiologic data on the impact of WBV exposures including dose response relationship, threshold exposure levels, and more robust cohort studies to evaluate effects are largely unavailable.<sup>1,16,17</sup>

Characterization of WBV exposure is important for more thoroughly describing risk and developing effective mitigation strategies.<sup>10</sup> Traditionally gold standard accelerometer (GSA) systems (high quality accelerometers and loggers) that follow the ISO standard for vibration measurement (ISO 2631-1) have been used which can be bulky, involve managing and protecting the accelerometer cables and can be expensive.<sup>18</sup> These systems have been used to evaluate WBV exposures to ensure compliance with European Union (EU) regulatory directives where applicable and for characterizing exposures as recommended in national and international standards.<sup>16,17,18</sup> Recently, relatively inexpensive compact Inertial Measurement Units (IMU) with built-in batteries and memory have emerged which may be used for collecting WBV exposures. While the ease of use of these new devices may allow for much more efficient collection of WBV exposure data, it is important to assess if the data provided from these devices are similar to those collected from traditional gold-standard devices. If lower cost, portable IMU devices have reasonable measurement accuracy, they may be suitable for field-based epidemiological measurements where there have historically been significant barriers to the installation and use of gold standard systems.<sup>19,20</sup> Specific scenarios in which use of these gold standard systems can be challenging include small enclosed environments without sufficient space for storage and implementation of the accelerometer, as well as airborne testing where the added weight of the device may be of concern. More broadly, the high cost and general lack of availability of testing systems limits the absolute number of tests that can be accomplished.<sup>20</sup> If IMU devices were able to be effectively

implemented to evaluate for WBV exposures, all of these potential barriers may be more effectively mitigated.

A variety of strategies exist to manage WBV exposures including controlling sources of vibration, substituting out equipment that presents higher exposure risks, engineering controls such as high performing seat suspension systems or specially designed vehicle tires to minimize vibration, administrative controls such as speed limits on gravel roads or job rotation to limit the overall time the vehicle operator is exposed, and personal protection equipment such as additional seat padding or shoes with vibration reducing soles.<sup>1,4,6,21</sup> In studies of US long haul truck drivers, use of seats designed to actively reduce vibration exposure reduced subjective low back pain by up to 30% and improved driver performance and other subjective concerns, showing that managing WBV exposures can improve occupational health outcomes.<sup>22,23</sup> For any of these mitigation strategies to be effective however, the exposure must first be identified and evaluated. As such, it is important to reduce barriers to WBV exposure measurement to allow for a more thorough characterization of these exposures, which may lead to the design and implementation of more effective mitigation strategies.

The purpose of this study was to determine if vibration measurements collected by an IMU device were significantly different from those collected by a GSA system in laboratory-based testing of known sinusoidal inputs and simulated vibration profile inputs in order to validate the use of an IMU device for testing of occupational WBV exposures.

## **Methods:**

### ***Sinusoidal Vibration Testing***

Using an accelerometer calibrator (Model 9110D, The Modal Shop, Cincinnati, OH) the vibration measurement accuracy of the GSA system (Rion DA-40 logger with a PCB 352C33 single axis accelerometer) and IMU device (Model AX-3, Axivity, Hoults Yard, UK) were compared. The sampling rates of the two systems were 1280 Hz for the GSA and 400 Hz for the IMU. The maximum G-levels for the GSA was set to +/- 40 g's and +/- 4 g's for the IMU device.

Using the accelerometer calibrator, each device was excited for 30 seconds with pure sinusoidal inputs at 5 different frequencies and up to 5 different amplitudes, spanning the frequency ranges and amplitudes most likely to be encountered during the measurement of WBV, with frequencies ranging from 2 Hz to 100 Hz and amplitudes ranging from 0.125 m/s<sup>2</sup> to 5.0 m/s<sup>2</sup>. As seen in Table 1, some high amplitude low frequency combinations were unable to be tested due to technical limitations of the accelerometer calibrator. The signals recorded by the devices were analyzed using a LabVIEW (LabVIEW version 16. National Instruments, Austin, TX, 1986-2019) program to generate corresponding outcome measures for each frequency and amplitude combinations measured.

The outcome measures of interest from each of these trials were the unweighted root mean square vibration (URMS) and the weighted acceleration equivalent value ( $A_{eq}$ ). The  $A_{eq}$  is used for WBV exposure assessment and has published recommended exposure limits.<sup>16,17,18</sup> The  $A_{eq}$  assigns a weighting factor to different vibration frequencies in accordance with ISO 2631-1 whole body vibration standard, with frequency values more associated with adverse health effects and matching or close to the resonant frequencies of structures in the body weighted higher. The

weighting factor associated with each frequency is shown in Figure 1. The errors from the known input values in the measurements of each system were compared using relative (% error) and absolute (mean error) errors. Differences in these errors were considered both in accordance with how these changes relate to the specific frequency and amplitude under consideration, and how the magnitude of the differences relate to acceptable measurement accuracy. Bland Altman analyses were also conducted to assess for statistical significance of the in inter-tool agreement between the IMU and GSA. The Bland Altman analysis is statistical test which compares measurements of the same dependent variable from two different measurement systems, and assess the degree of agreement by evaluating the bias, range and dispersion of the differences between the two systems.<sup>24,25</sup> The null hypothesis for these analyses is that the mean of the differences of each paired measurement is zero, and the alternative hypothesis is that the mean of the differences of each paired measurement is nonzero. Statistical analysis was performed using JMP (JMP®, Version 14. SAS Institute Inc., Cary, NC, 1989-2019). A priori limits for acceptable relative error from the known vibration magnitude of 10% or less was deemed to be an acceptable margin of error for the purposes of occupational WBV exposure assessment.

### ***Random Vibration Testing***

For the next phase of the study, a GSA system consisting of two accelerometers and two IMU devices were mounted on a single degree of freedom (Z-axis) shaker table, with one GSA/IMU pair mounted to the base/floor of the shaker table and the other pair mounted at the top of a seat which had a built-in suspension system. Only the Z-axis data from the various systems were analyzed. The sampling rates of the two systems were 1280 Hz for the GSA and 400 Hz for the IMU. The maximum G-levels for the GSA was set to +/- 40 g's and +/- 4 g's for the IMU device. Two field-collected random vibration profiles from the floor of an SUV were then recreated by the

shaker table, with four unique trials from a cobblestone road (high frequency, low amplitude vibration) and four unique trials from a very rough road (high amplitude, low frequency vibration). The signals recorded from these devices were analyzed using a LabVIEW program (LabVIEW version 16. National Instruments, Austin, TX, 1986-2019) to generate corresponding outcome measures for each trial. From these simulations vertical, Z-axis  $A_{eq}$  and Vibration Dose Value (VDV) vibration measures were collected from each system at the floor of the shaker table and from the top of the seat suspension. The VDV value is a weighted cumulative measure of vibration exposure that is preferred in exposure scenarios characterized by intermittent shocks rather than steady vibration exposure, and has published recommended occupational exposure standards.<sup>16,17,18</sup> The relative and absolute differences between the measurements of the IMU device and GSA were assessed for the two vibration parameters ( $A_{eq}$  and VDV) and the two location (floor and suspension top). Due to only having four measurements per road type, Bland Altman analyses were not performed. Statistical analysis was performed using JMP (JMP®, Version 14. SAS Institute Inc., Cary, NC, 1989-2019). A priori limits for acceptable relative difference in measurements between the two systems of 10% or less was deemed to be an acceptable margin of error for the purposes of occupational WBV exposure assessment.

## Results:

For sinusoidal testing using the accelerometer calibrator, Table 1 shows the URMS measurements and their errors across the range of frequencies and amplitude in both absolute and relative terms for the Z-axis. The grand mean unweighted absolute errors of the GSA system and IMU device were  $0.003 \text{ m/s}^2$  and  $-0.081 \text{ m/s}^2$  respectively, and on the relative scale were 0.2% and -7.6% respectively. Table 2 shows the  $A_{eq}$  (weighted) measurements and their errors across the range of frequencies and amplitudes in both absolute and relative terms for the Z-axis. The grand mean weighted absolute errors of the GSA system and IMU device were  $0.005 \text{ m/s}^2$  and  $0.006 \text{ m/s}^2$  respectively, and on the relative scale were 0.9% and 1.2% respectively. The IMU device had its largest error in the 100 Hz domain in the URMS measure of -8.1%, which was significantly reduced by weighting in the  $A_{eq}$  measure to 1.0%. Analysis of the X-axis and Y-axis measures were similar in magnitude to the Z-axis and below the a priori 10% error limit. Figure 2 shows the results of the Bland-Altman analysis for inter-tool agreement between the systems on the unweighted scale with no statistically significant difference in measurements of either tool for the URMS measure (mean difference  $0.084 \text{ m/s}^2$ ,  $p=0.19$ ). Figure 3 shows the Bland-Altman analysis for inter-tool agreement between the systems for the weighted  $A_{eq}$  measure with no statistically significant difference in measurements of either tool (mean difference  $-0.001 \text{ m/s}^2$ ,  $p=0.95$ ).

For testing using random vibration profiles, Figure 4 shows that the difference in the weighted  $A_{eq}$  measure between measurements for the rough road was  $0.15 \text{ m/s}^2$  (4.9%) at the floor and  $0.04 \text{ m/s}^2$  (9.9%) at the suspension top. For the cobblestone road, the weighted difference was  $0.03 \text{ m/s}^2$  (1.4%) at the floor and  $0.006 \text{ m/s}^2$  (2.2%) at the suspension top. The overall average difference across both road types and measurement locations was  $0.06 \text{ m/s}^2$  (4.6%). Figure 5 shows the difference in the weighted VDV measure between measurements for each road type.

The difference in the weighted VDV for the rough road was  $3.9 \text{ m/s}^{1.75}$  (6.2%) at the floor and  $0.7 \text{ m/s}^{1.75}$  (8.5%) at the suspension top. For the cobblestone road, the weighted difference was  $0.30 \text{ m/s}^2$  (0.8%) at the floor and  $0.06 \text{ m/s}^2$  (1.1%) at the suspension top. The overall average difference between road types and measurement locations was  $1.2 \text{ m/s}^{1.75}$  (4.1%).

## **Discussion:**

The purpose of this study was to determine if new low cost, versatile IMU devices have acceptable WBV measurement accuracy as compared to current GSA systems. GSA systems present some important barriers to routine use in the collection of WBV exposure data. If the less expensive IMU devices were able to measure WBV exposures with acceptable accuracy, these less complicated devices could have a wide range of applications in assessing occupational WBV exposures to better understand and control the health risks associated with WBV exposure.

The results of accelerometer calibrator testing show that the IMU device has acceptable measurement accuracy to known vibration magnitudes. The errors of the IMU device fell under the pre-determined a priori 10% limits for both the URMS and  $A_{eq}$  measures. In addition, the weighted  $A_{eq}$  measures had a considerably smaller grand mean error than the unweighted URMS measure (-7.6% vs 1.2%). Analysis of the errors by frequency domain suggests the accuracy of the IMU device may decrease somewhat at the extremes of the frequency distribution (predominantly measures at 100 Hz) with the URMS measures, fortunately, these IMU errors were substantially reduced with the weighted  $A_{eq}$  occupational measures (-8.1% vs 1.0%). A potential source of the URMS error at 100 Hz could be the lower sampling rate of the IMU device (400 Hz vs 1280 Hz). Additionally, the accelerometer calibrator used was not certified for use below 5 Hz, so the validity of results in the 2 Hz domain may have been compromised.<sup>26</sup> Additionally, in accelerometer calibrator testing, there was no statistically significant difference in the measurements between the IMU device and GSA system using the Bland-Altman analysis, indicating there was no difference between the devices for measuring the sinusoidal accelerations over the relevant frequency ranges for occupational WBV exposures.

In random vibration profile testing, the relative differences in weighted occupational vibration measurements were less than the a priori threshold of 10% in all scenarios, with an average relative difference of 4.6% and 4.1% respectively for the  $A_{eq}$  and VDV measurements. These findings suggest that the IMU device may be an acceptable replacement for GSA systems.<sup>16,17,18</sup>

To build further knowledge on the use of IMU devices in WBV exposure assessment, next steps include further testing of a variety simulated vibration profiles, for differing types of occupational exposure to WBV, and implementing these technologies in real world WBV exposure scenarios. These steps would help to validate the findings of this study over a wide range of measurement scenarios and determine if there are certain occupations or tasks in which the IMU device might not perform as well as a GSA system. Testing with the accelerometer calibrator identified greater discrepancies between the GSA system and IMU device at higher frequencies (predominantly 100 Hz), the high frequencies are well above the frequencies encountered in most occupational scenarios (2 – 30 Hz).<sup>3</sup> However, the IMU devices should still be validated in a variety of simulated vibration profile and real-world collection scenarios.

If further studies continue to show appropriate measurement accuracy of IMU devices, there are multiple important applications where these units could be utilized. One important application would simply be allowing much easier and broader collection of real-world WBV exposure data, allowing for much more detailed characterizations of how WBV exposures vary by terrain type, weather, vehicle suspension, and a host of other variables. Furthermore, because these devices would greatly increase the ability to gather data longitudinally for occupational exposures to WBV, cohort studies of exposed workers could be conducted to better assess health effects associated with these WBV exposures, and more thoroughly define the dangerous levels or types

of exposures. If these types of longitudinal cohort studies could be accomplished, more effective mitigation strategies for WBV could be identified and implemented. Some administrative strategies include but are not limited to device monitoring for personal WBV exposure levels to ensure individual workers remain at safe exposure levels over the course of their career, as well as better understanding of the WBV exposure associated with specific work tasks, allowing for better rotation of individuals among these high exposure tasks. Engineering controls could also be better introduced such as designing seats, suspensions, or other WBV reducing systems that are tailored to specifically reduce the most hazardous forms of WBV exposure for any targeted occupational scenario, potentially interventions could be designed with modularity such that these mitigation strategies could be interchanged with changing exposure scenarios.

There are several important limitations to this study that could be addressed through further studies. Only a limited sample of simulated vibration profiles, and no real-world measurement scenarios were performed as part of this study. As previously discussed, IMU devices should be further investigated across a wide spectrum of potential WBV exposure scenarios, to include scenarios with random high impulse moments. Such studies could serve to further validate the efficacy of the IMU device for real world testing. Also, in the vibration profile testing, only single axis exposures were evaluated. In order to replicate real world vibration exposure testing, the measurements of these systems should be evaluated real-world tri-axial exposures. Additionally, only one IMU sampling frequency was evaluated (400 Hz), and the slower sample rate of the IMU device may explain all or part of the URMS errors at 100 Hz in the sinusoidal testing. Further studies could evaluate the measurement accuracy of the IMU at higher sampling rates (e.g., 800 or 1600 Hz), and determine whether and in what scenarios higher sampling rates are needed. Finally, the accelerometer calibrator used in the study was not designed to operate at frequencies lower

than 5 Hz, as a result, the 2 Hz results may not be as robust as the other frequencies. If future studies are designed to evaluate vibrations at this frequency, equipment designed to operate under these low frequency conditions should be used.

In conclusion, initial evaluation of the measurement accuracy of an IMU device in a laboratory-based environment shows promising results with acceptable measurement accuracy to known values, and agreement with GSA technologies. Based on these results, IMU devices may be acceptable for use in measuring occupational WBV exposure and could lead to greatly reducing barriers in the consistent testing of these exposures.

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Table 1: Mean Z-axis measurements and absolute and relative errors by amplitude and frequency of the unweighted URMS vibration for the two measurement systems.

Amplitude	2 Hz		8 Hz		16 Hz		32 Hz		100 Hz		Abs Error		Rel Error	
	Acc	IMU	Acc	IMU	Acc	IMU	Acc	IMU	Acc	IMU	Acc	IMU	Acc	IMU
<b>0.125</b>	0.117	0.143	0.124	0.142	0.125	0.140	0.125	0.136	0.124	0.112	-0.002	0.009	-1.5%	7.5%
<b>0.25</b>	0.239	0.267	0.250	0.268	0.251	0.267	0.251	0.256	0.248	0.199	-0.002	0.002	-0.9%	0.6%
<b>0.50</b>	0.483	0.503	0.503	0.509	0.505	0.504	0.505	0.487	0.499	0.368	-0.001	-0.026	-0.2%	-5.2%
<b>1.00</b>	—	—	1.011	1.020	1.012	1.010	1.006	0.979	0.999	0.723	0.007	-0.067	0.7%	-6.7%
<b>5.00</b>	—	—	—	—	5.069	5.025	5.001	4.900	4.984	3.631	0.018	-0.481	0.4%	-9.6%
<b>Abs Error</b>	-0.003	0.005	0.000	-0.005	0.005	-0.020	0.005	-0.026	0.004	-0.103	<b>0.003</b>	<b>-0.081</b>	—	—
<b>Rel Error</b>	-1.6%	2.4%	-0.1%	-1.4%	0.6%	-2.7%	0.5%	-2.6%	0.3%	-8.1%	—	—	<b>0.2%</b>	<b>-7.6%</b>

Table 2: Mean Z-axis measurements and absolute and relative errors by amplitude and frequency of the weighted  $A_{eq}$  vibration for the two measurement systems

Amplitude	2 Hz		8 Hz		16 Hz		32 Hz		100 Hz		Abs Error		Rel Error	
	Acc	IMU	Acc	IMU	Acc	IMU	Acc	IMU	Acc	IMU	Acc	IMU	Acc	IMU
<b>0.125</b>	0.065	0.076	0.127	0.133	0.095	0.099	0.050	0.053	0.013	0.027	0.000	0.007	-0.5%	10.6%
<b>0.25</b>	0.139	0.152	0.258	0.271	0.193	0.200	0.100	0.100	0.023	0.029	0.002	0.010	1.2%	6.9%
<b>0.50</b>	0.277	0.279	0.521	0.523	0.388	0.384	0.201	0.190	0.044	0.035	0.004	0.001	1.6%	0.3%
<b>1.00</b>	—	—	1.047	1.367	0.778	0.772	0.400	0.383	0.087	0.056	0.006	0.072	0.9%	12.6%
<b>5.00</b>	—	—	—	—	3.893	3.846	1.989	1.915	0.433	0.254	0.016	-0.084	0.8%	-4.0%
<b>Abs Error</b>	0.002	0.009	0.003	0.027	0.006	0.020	0.006	0.016	0.006	0.006	<b>0.005</b>	<b>0.006</b>	—	—
<b>Rel Error</b>	1.5%	7.7%	1.2%	11.9%	1.3%	4.4%	1.0%	2.8%	1.0%	1.0%	—	—	<b>0.9%</b>	<b>1.2%</b>

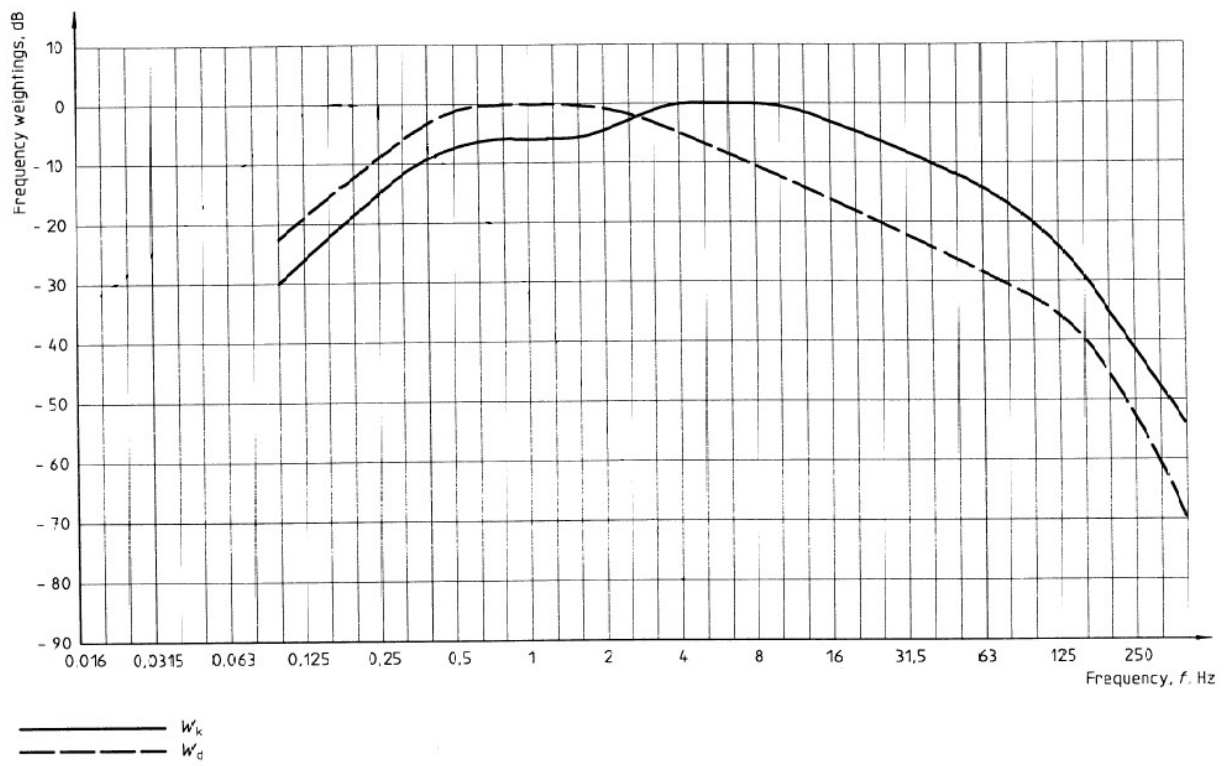


Figure 1: ISO 2631-1 frequency weighting curves for vertical ( $W_k$ ) and horizontal ( $W_d$ ) measurements in the recumbent position

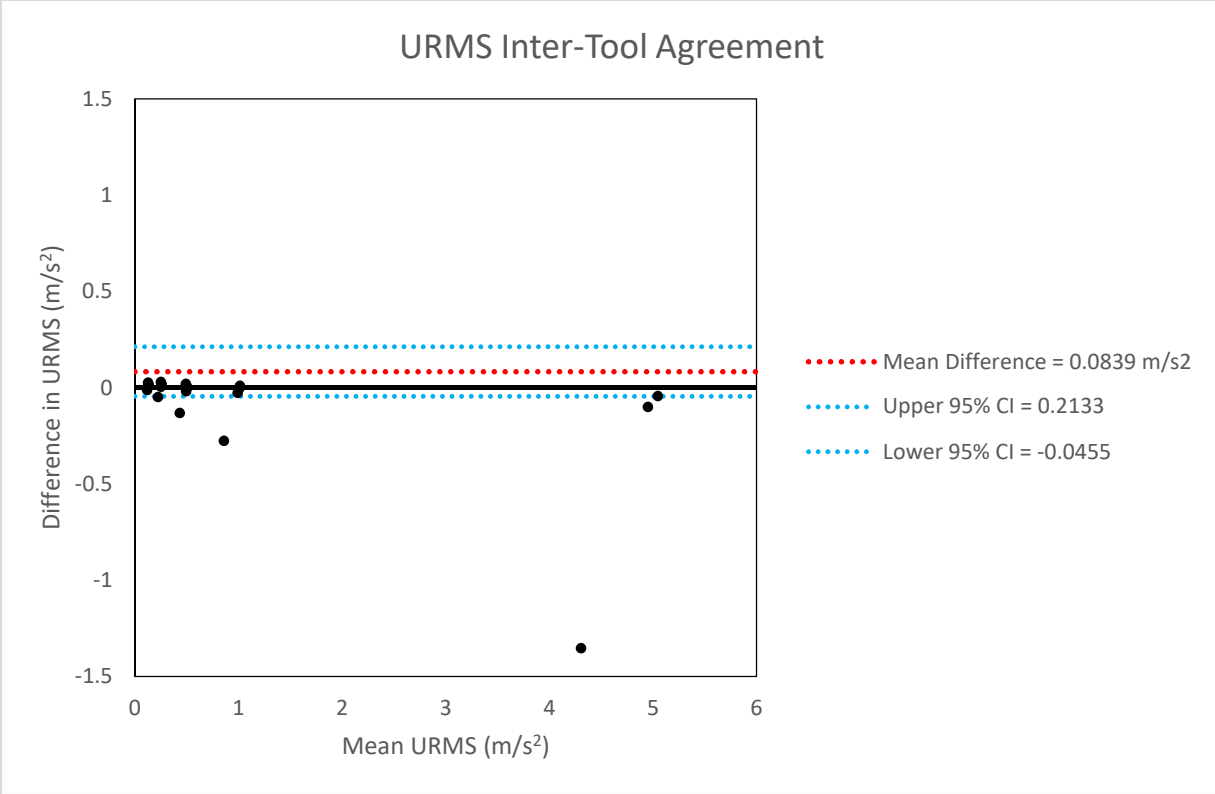


Figure 2: Bland-Altman analysis of URMS measurement agreement between IMU device and GSA in Z-axis accelerometer calibrator testing ( $p=0.19$ )

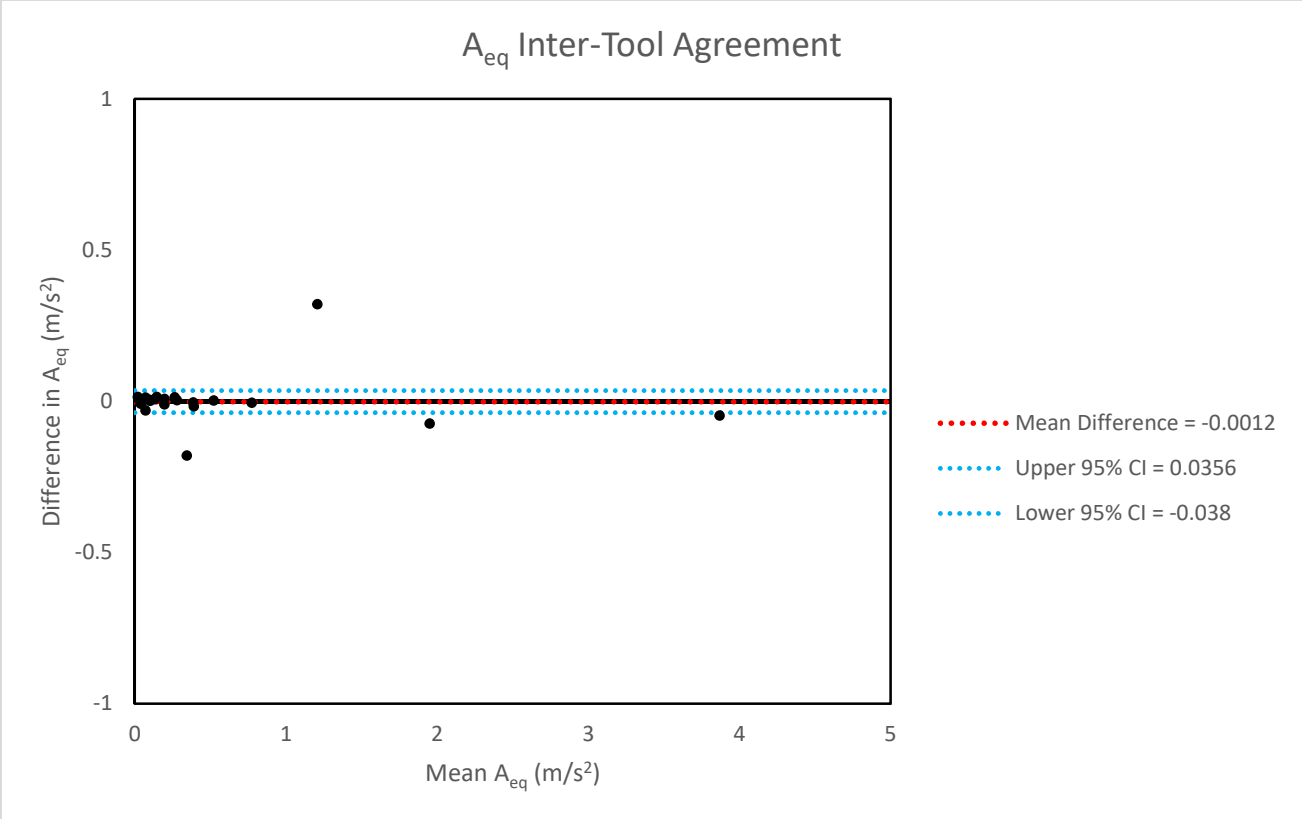


Figure 3: Bland-Altman analysis of A<sub>eq</sub> measurement agreement between IMU device and GSA in Z-axis accelerometer calibrator testing ( $p = 0.95$ )

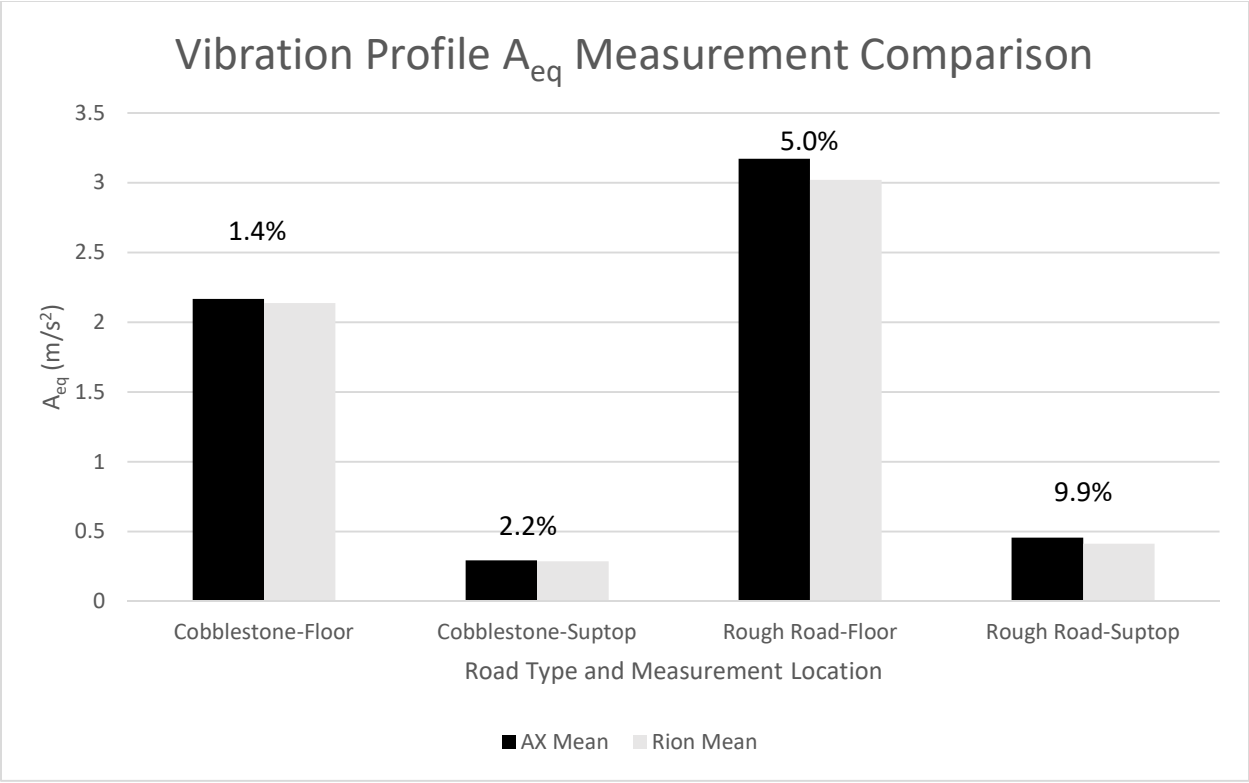


Figure 4: Differences in  $A_{eq}$  measure for vibration profile and measurement location, overall difference  $0.06 m/s^2$  (4.6%)

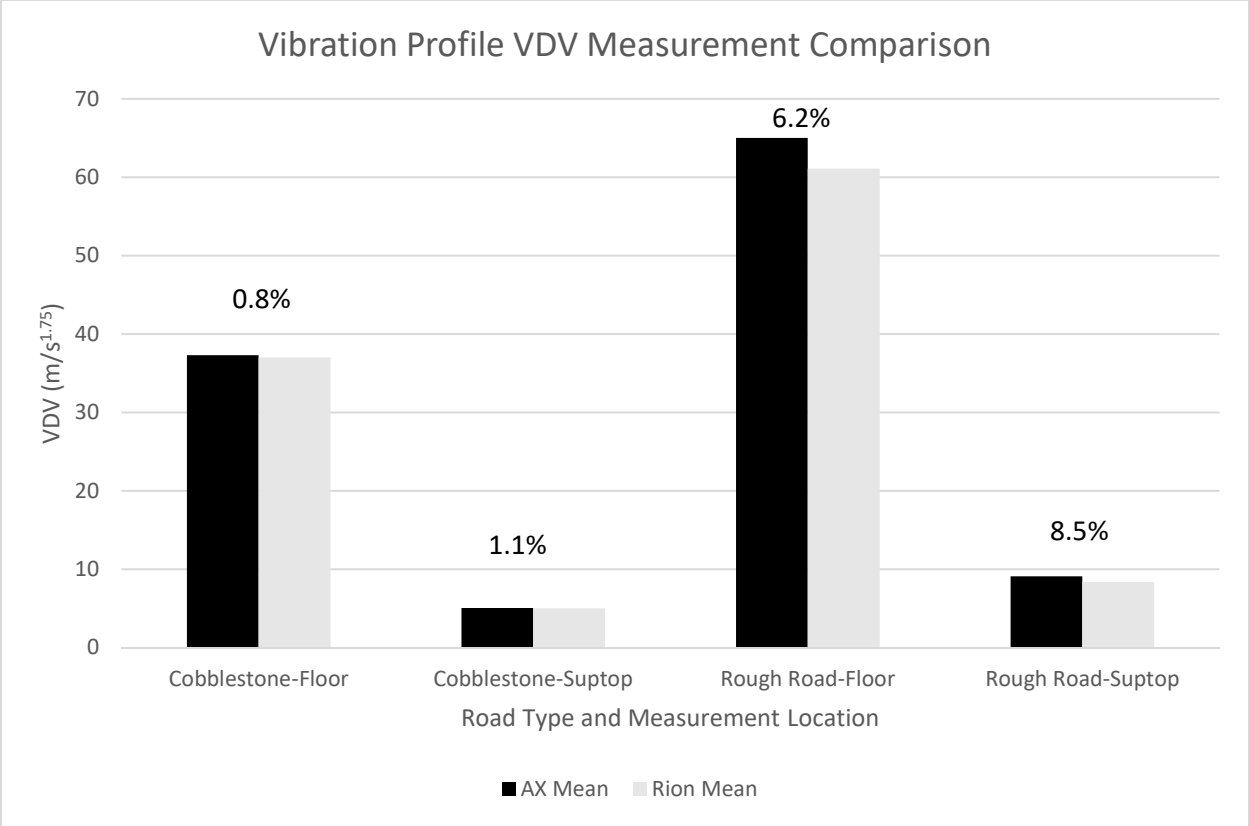


Figure 5: Differences in VDV measure for vibration profile and measurement location, overall difference 1.2 m/s<sup>1.75</sup> (4.1%)