Coal Services Health & Safety Trust project 20624

Developing and validating an affordable whole body vibration measurement device

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Executive Summary

Long term exposure to whole-body vibration is a known cause of back pain and other adverse health effects. Exposure to vibration also contributes to operator fatigue and discomfort, and may interfere with task performance. Many operators of mobile plant and equipment used in surface and underground mines across the whole industry are exposed to significant whole-body vibration for relatively long periods.

The aim of the project is to develop and validate an iOS application to convert an iPod Touch into an affordable whole body vibration measurement tool which will enable surface coal mines to gather the data necessary to effectively manage this health hazard.

A prototype application was previously developed with funding provided by Rio Tinto Coal Australia. Laboratory testing of the iPod Touch hardware; testing of the prototype software through comparisons of measurements taken with gold standard devices while driving light vehicles over a range of roadway conditions; and 58 pairs of measurements taken from a range of heavy vehicles in operation at three surface coal mines confirmed that the accelerometer data obtained via an iPod has potential to provide a sufficiently accurate measure of whole body vibration exposure to be useful in identifying and evaluating control measures to reduce whole body vibration exposure at surface mine sites. A paper describing the results of the laboratory and light vehicle testing of the prototype application has been published in the *Journal of Occupational and Environmental Hygiene*; and a paper describing the heavy vehicle data has been published in the *Annals of Occupational Hygiene*. The application, user manual, and training materials are available for free download via the project website (ergonomics.uq.edu.au/wbv).

Additional validity and usability testing has been undertaken at a central Queensland coal mine, including the successful use of the application on 30 iPods to collect 61 samples of "whole-shift" data from nine equipment types over three days. The relatively low cost of the iPod Touch hardware, and simplicity of the WBV application, has the potential to facilitate routine collection of whole-body vibration exposure by site-based workplace safety and health staff as part of a systematic whole-body vibration risk management program. The ability to respond rapidly to operator feedback or complaints may also allow early identification of developing problems with roadways or equipment.

As well as allowing valid assessments of health risks to be undertaken at a workplace, identifying the combinations of factors which lead to elevated vibration amplitudes provides valuable insight into the potential means of implementing effective risk control interventions. The ability to easily collect whole-body vibration data allows the potential effectiveness of suggested control measures to be assessed as part of the risk management process. In sum, the WBV application has potential to be used to effectively evaluate whole-body vibration exposure within a workplace risk management process.

Background

The resonant frequency of the human spine is about five Hz[1]. Unfortunately, this corresponds rather well with the frequency components of accelerations transmitted to seated operators of a wide range of mobile plant and equipment used in the mining industry[2]. Long term exposure to whole-body vibration is a known risk factor for the subsequent development of back pain[3-6]. Other health effects associated with whole-body vibration include adverse consequences for cardiovascular, respiratory, digestive, reproductive, endocrine and metabolic systems. Exposure to high amplitude vibration also contributes to operator fatigue and discomfort, and may interfere with task performance[7].

Many operators of mobile plant and equipment used in surface and underground mines across the whole industry are exposed to significant whole-body vibration for relatively long periods[8-13]. The vibration exposures experienced by mining equipment operators are a function of many variables including: equipment design; seat design, condition and adjustment; roadway conditions; vehicle maintenance; activity being undertaken; and driver behaviour[14]. Many of these variables are dynamic, varying over time scales ranging from hours (eg., activity), days (roadway conditions, seat adjustment), months (vehicle maintenance) or years (equipment design).

Figure 1 illustrates the root mean square (r.m.s.) and Vibration Dose Value (VDV) expressed as an 8 hour equivalent (VDV[8]) measures of whole-body vibration obtained from twenty-six dozers in operation at a Queensland surface coal mine. The r.m.s. is a measure of the average vibration amplitude over the whole sample, while the VDV is more heavily influenced by high amplitude acceleration peaks. The range of values obtained from similar equipment performing similar tasks at the same mine demonstrates the potential to identify the sources of this variability as a means of identifying opportunities for reducing vibration amplitude. Control measures which have been explored in other industries include: operator training, limiting vehicle speed, road maintenance, maintenance of vehicle suspension and seating, seating design and seat adjustment[15-17].

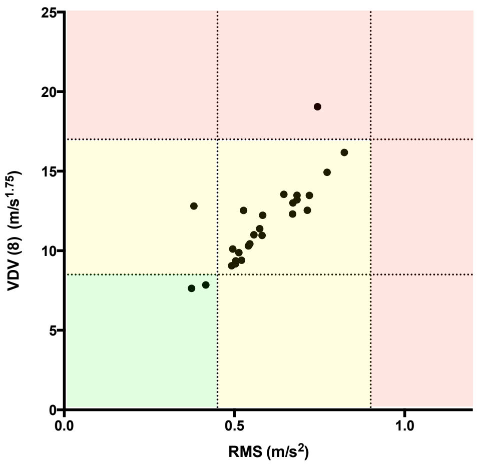


Figure 1: Vertical acceleration amplitudes experienced by 26 operators of dozers at a surface coal mine (Burgess-Limerick, 2012[8]).

Measurement of whole-body vibration currently requires expensive ($4,500 to $10,000) equipment (Figure 2) consisting of triaxial accelerometer mounted within a seat pad and connected by cable to an acquisition and analysis module. As well as being expensive and relatively fragile, the interfaces are complex and considerable training is required to enable data to be collected and interpreted. Mining operations consequently undertake measurement of whole-body vibration infrequently. Such ad hoc measurements are unlikely to provide a reliable indication of the vibration exposures of equipment operators and do not provide the information required by mine sites to effectively manage whole-body vibration exposures. An opportunity exists to provide a simple and inexpensive whole-body vibration measurement device which will enable the collection of the information required to manage exposure to this hazard.

Figure 2: Commercially available whole-body vibration measurement equipment.

A 16Gb iPod Touch (Figure 4) costing $249 incorporates a triaxial accelerometer (model STM LIS302DL) which provides measurements of sufficient sensitivity and range to assess whole-body vibration. The 86g device can digitise and store more than 1000 hours of accelerometer data. After filtering the acceleration data, summary measures (r.m.s & VDV) can be calculated by an iOS application and presented in comparison to the "health guidance caution zones" provided in ISO2631.1.

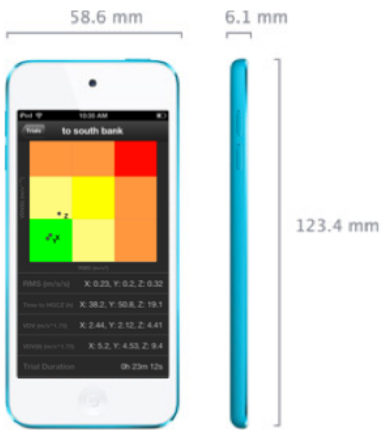


Figure 3: 16 Gb iPod Touch

Following proof of concept, a prototype of an iOS application (WBV) to record and analyse whole-body vibration was developed with seed funding provided by Rio Tinto Coal Australia.

Project Aim

The aim of the project is to develop and validate an iOS application to convert an iPod Touch into an affordable whole body vibration measurement tool. This application will enable surface coal mines to easily gather the surveillance data necessary to identify and evaluate effective control measures.

Project Outline

1. Collect WBV data simultaneously using SV106 human vibration meter and analyser and prototype WBVpod application from the range of equipment types in use at surface coal mines.

2. Undertake analysis of these data to identify the filter characteristics required to optimise the match between SV106 and ipod accelerometer results for root mean square (rms) and vibration dose value (VDV) measures of vibration amplitude (as defined in ISO2631-1) in vertical (Z) and horizontal (X, Y) directions.

3. Develop a user-friendly ipod touch application which collects and evaluates whole body vibration in X, Y & Z directions, provides summary outcomes (rms, VDV[8]) and interpretations with respect to the Health Guidance Caution Zone, and allows logged data to be downloaded via web browser.

4. Develop a short users manual and associated training materials which explains the use of the measurement tool and interpretation of the results.

5. Trial the WBVpod with operators of surface coal mining equipment to ensure usability and revise as necessary.

6. Make application, users manual and training materials available for download.

Outcomes

Laboratory testing

The prototype application collects three dimensional accelerometer data at a nominal inter-sample interval of 0.01s. Accelerometer data were collected from each of five iPod touch devices while placed on a SV111 (Svantek Sp., Warsaw, Poland) calibrator which provides a vertical 1 m/s^2 r.m.s. vibration at 15.9 Hz. Accelerometer data were downloaded from the iPod Touch to personal computer and the r.m.s. acceleration values calculated for the vertical direction data.

Although the inter-sample interval was set to the minimum value (0.01s) within the application, the actual inter-sample intervals were slightly higher on average, and somewhat variable. Figure 4 illustrates the typical variability of the inter-sample interval over a 5 second period. The actual average sampling rate achieved varied from 88 Hz to 92 Hz across trials and iPods. This variability in sampling rate is not unique to the iPod touch, having been also reported in android devices[18]. The sampling rate limitations and variability in sampling rate is likely to be the principal source of any inaccuracies in the estimation of whole body vibration in comparison to gold standard devices which sample at rates of the order of 8 kHz.

An example of Z direction accelerometer data gathered from an iPod Touch placed on the SV111 calibrator is provided in Figure 5. These data provide an approximation of the 1 m/s^2 r.m.s. vibration at 15.9 Hz provided by the calibrator within the limitations of the sampling rate and noise inherent to the device. The average amplitude (r.m.s.) of the acceleration data collected by five iPod touch devices was 0.962 m/s^2, an average constant error of -0.038 m/s^2.

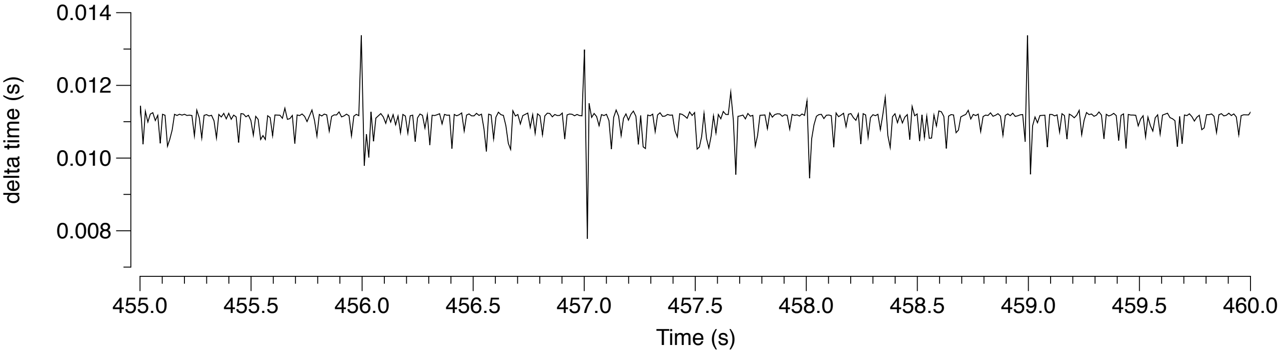


Figure 4: Inter-sample interval illustrating the variability in sampling rate of prototype WBV application.

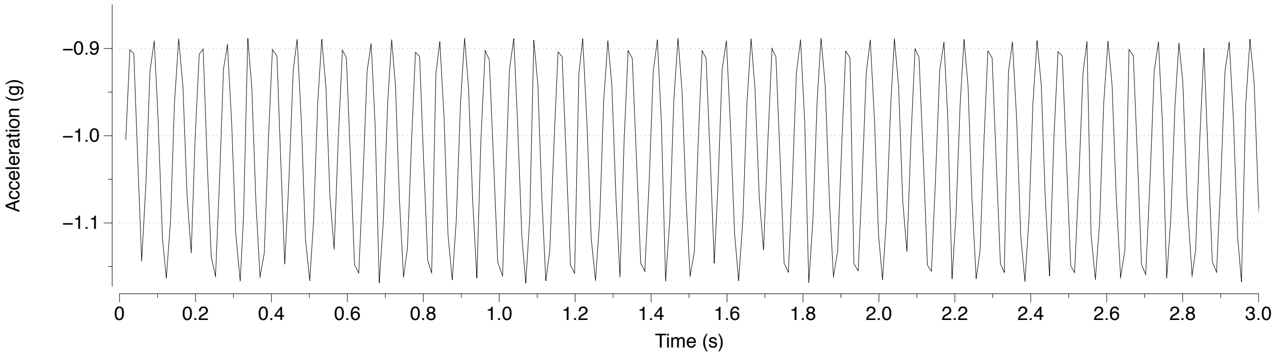


Figure 5: Vertical acceleration data recorded by prototype application while placed on 1 m/s^2 calibrator vibrating at 15.9 Hz.

Light vehicle testing

Three dimensional accelerometer data were gathered simultaneously from 5th generation iPod touch devices placed under the seat pad accelerometer of a gold standard vibration measurement device placed on the driver's seat while four different light vehicles were driven in a range of environments (highway, suburban streets, gravel roads & off road). Two gold standard measurement devices were employed, SV106 (Svantek Sp., Warsaw, Poland) and a Type 4447 Human Vibration Analyzer (Brüel & Kjær Sound & Vibration Measurement A/S, Nærum, Denmark). Forty-two trials ranging in duration from 10 to 55 minutes (median 15 minutes) were recorded.

The accelerometer data were subsequently downloaded and filtered according to the Wk and Wd weightings specified by ISO2631.1 for vertical and horizontal accelerations respectively using Matlab (Mathworks Inc, Natick, MA)[19]. The r.m.s. amplitudes of these data were compared with the corresponding r.m.s. values calculated by the gold standard devices though the calculation of constant and absolute errors.

Accelerometer data for the vertical direction gathered simultaneously from an iPod Touch and gold standard vibration measurement devices are illustrated in Figure 6. The mean absolute error across the 42 trials was 0.019 m/s^2 for the vertical direction and slightly higher for fore-aft and side-to-side accelerations (0.02 m/s^2 & 0.015 m/s^2 respectively). Figure 7 reveals that the pattern of constant error as a function of acceleration amplitude suggests that the acceleration data recorded from the iPod touch while driving light vehicles were increasingly likely to underestimate the true vibration magnitude as the vibration amplitude increased, however the magnitude of the error was 0.073 m/s^2 or less for vertical acceleration values up to 0.8 m/s^2 r.m.s.

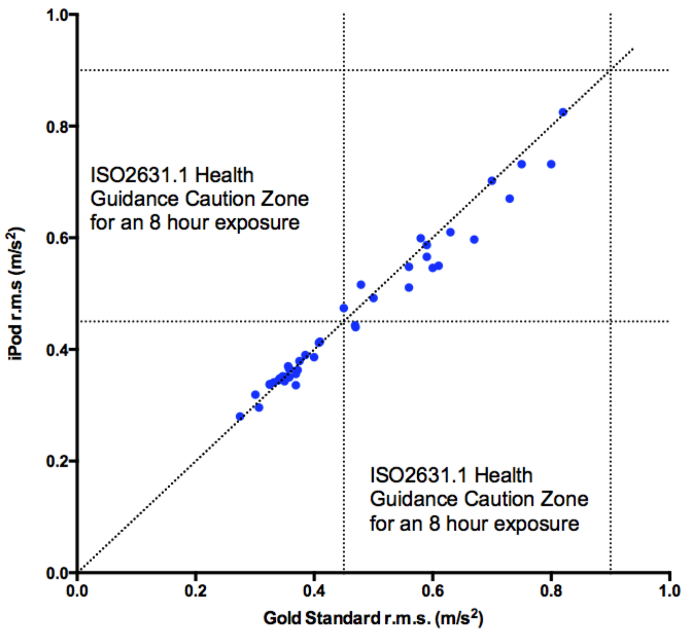


Figure 6: Vertical acceleration data (r.m.s) obtained from the prototype application compared with the values obtained simultaneously from gold standard devices while driving light vehicles in a range of roadway conditions.

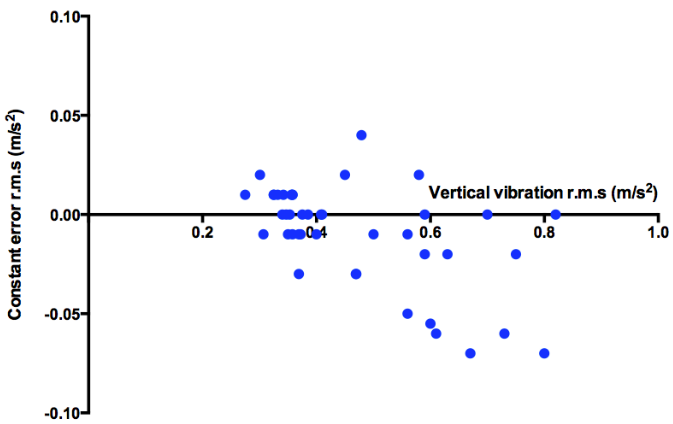


Figure 7: Constant error (iPod prototype - gold standard) for vertical acceleration measurements (r.m.s) as a function of the gold standard measured values obtained while driving light vehicles in a range of roadway conditions.

Heavy vehicle testing

Three dimensional accelerometer data were gathered simultaneously from 5th generation iPod touch devices placed under the seat pad accelerometer of a gold standard vibration measurement device placed on the driver's seat of heavy mining equipment whilst operators performed their normal duties. Twenty-six pairs of measurements measured simultaneously via Larson Davis Human Vibration Meter 100 (PCB Piezotronics, Inc, Depew, New York, USA) and the WBV prototype were obtained from a range of heavy equipment (Dozers, Graders, Excavators, Loaders, Haul trucks) at two Rio Tinto Coal surface coal mines. A further thirty-two pairs of measurements were obtained from SV106 (Svantek Sp., Warsaw, Poland) and the iPost Touch from a range of heavy equipment (Haul trucks, Excavator, Loaders) in operation at Boggerbri Mine. Measurement duration ranged from 12 minutes to 54 minutes (median = 29 minutes). Figures 8-10 present the gold standard measurements (r.m.s and VDV[8]) as a function of equipment type.

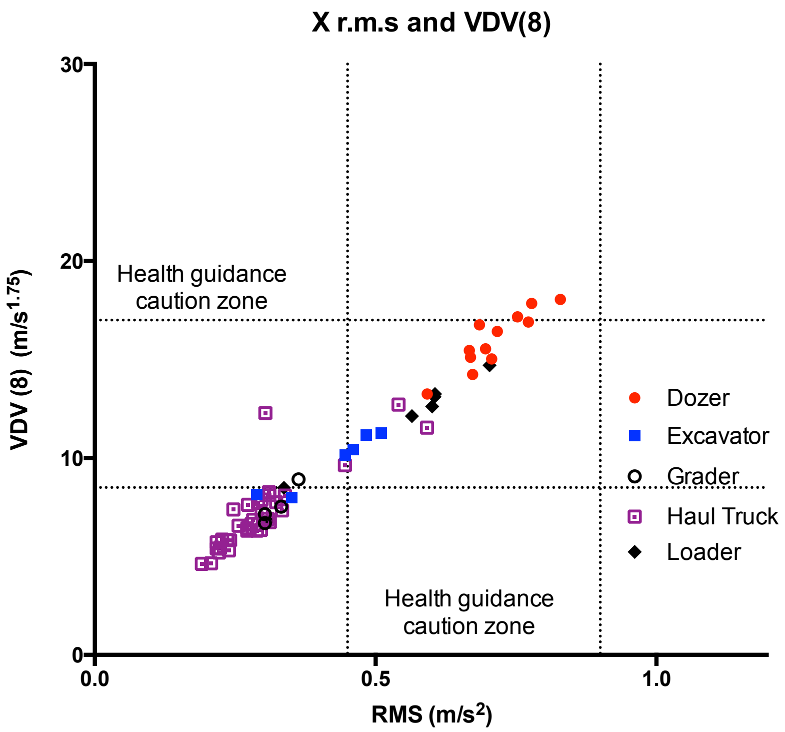


Figure 8: X direction (fore-aft) whole body vibration measurements from heavy equipment in use at three surface coal mines

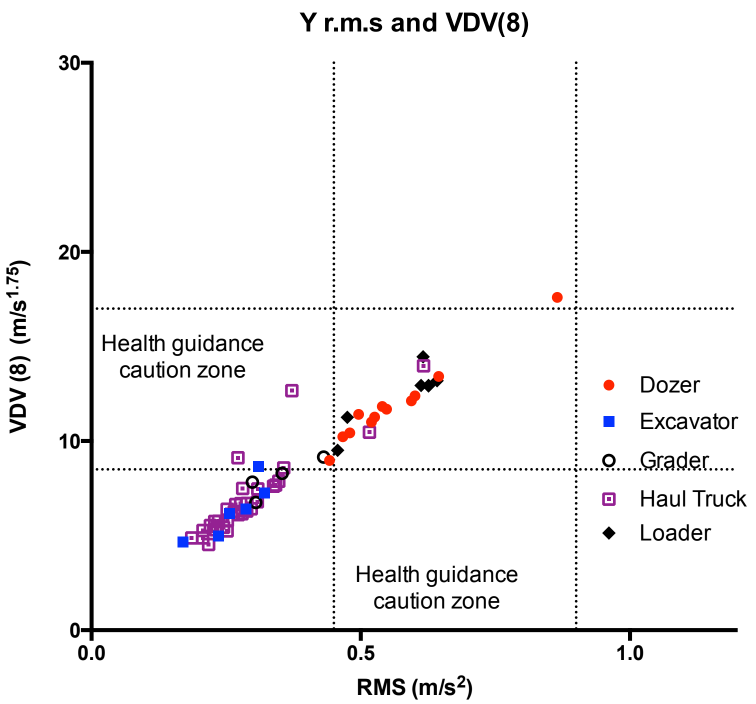


Figure 9: Y direction (side-to-side) whole body vibration measurements from heavy equipment in use at three surface coal mines

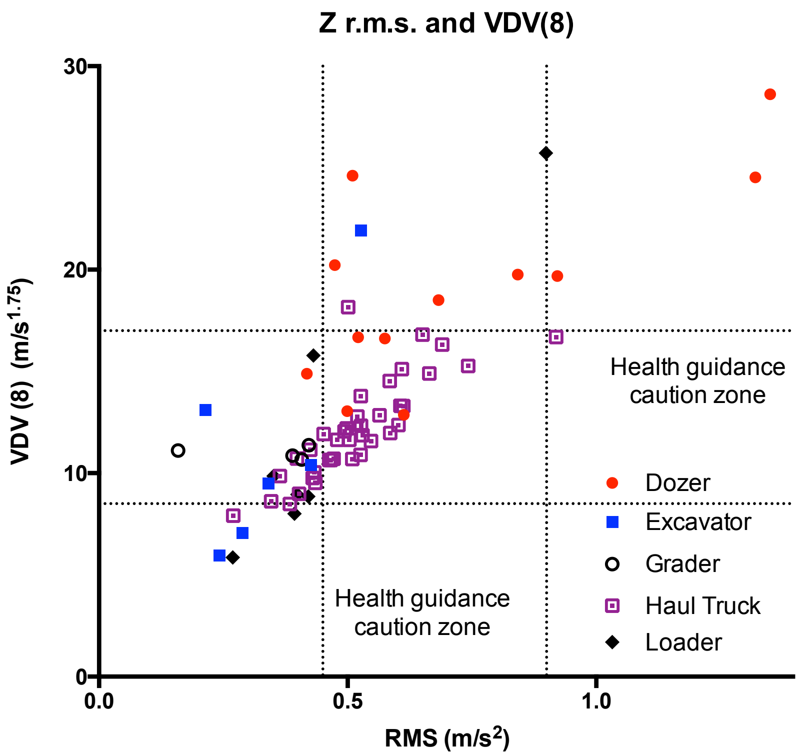


Figure 10: Y direction (side-to-side) whole body vibration measurements from heavy equipment in use at three surface coal mines

These results are consistent with previous research in finding that many pieces of heavy equipment in operation at surface mine sites expose operators to vibration levels which lie within, or exceed, the health guidance caution zone defined by ISO 2631.1 for eight hour shift durations.

The iPod accelerometer data were subsequently downloaded and filtered according to the Wk and Wd weightings specified by IS02631.1 for vertical and horizontal accelerations respectively using Matlab (Mathworks Inc, Natick, MA)[19]. The r.m.s. and VDV(8) measurements calculated from the prototype application were compared with the corresponding values calculated from the gold standard devices. Figures 11 - 16 illustrate these comparisons and present constant error data as a function of the gold standard measurement for these heavy vehicle measurements. The light vehicle data obtained previously are also displayed for comparison.

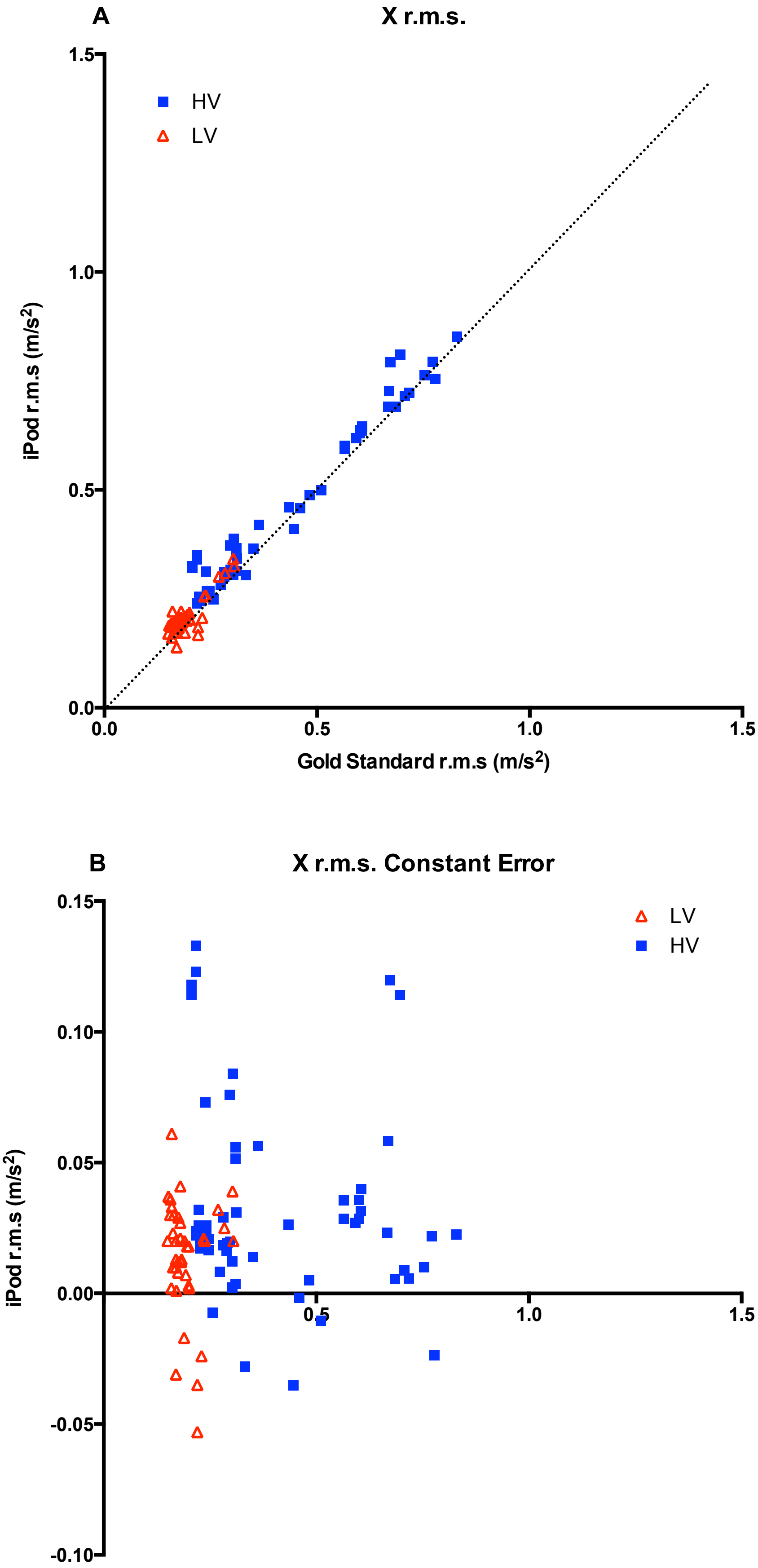


Figure 11: X direction (fore-aft) accelerations (r.m.s) for heavy and light vehicles. Upper panel (A) presents iPod measured data as a function of gold standard measured values. Lower panel (B) presents constant error as a function of gold standard measured values.

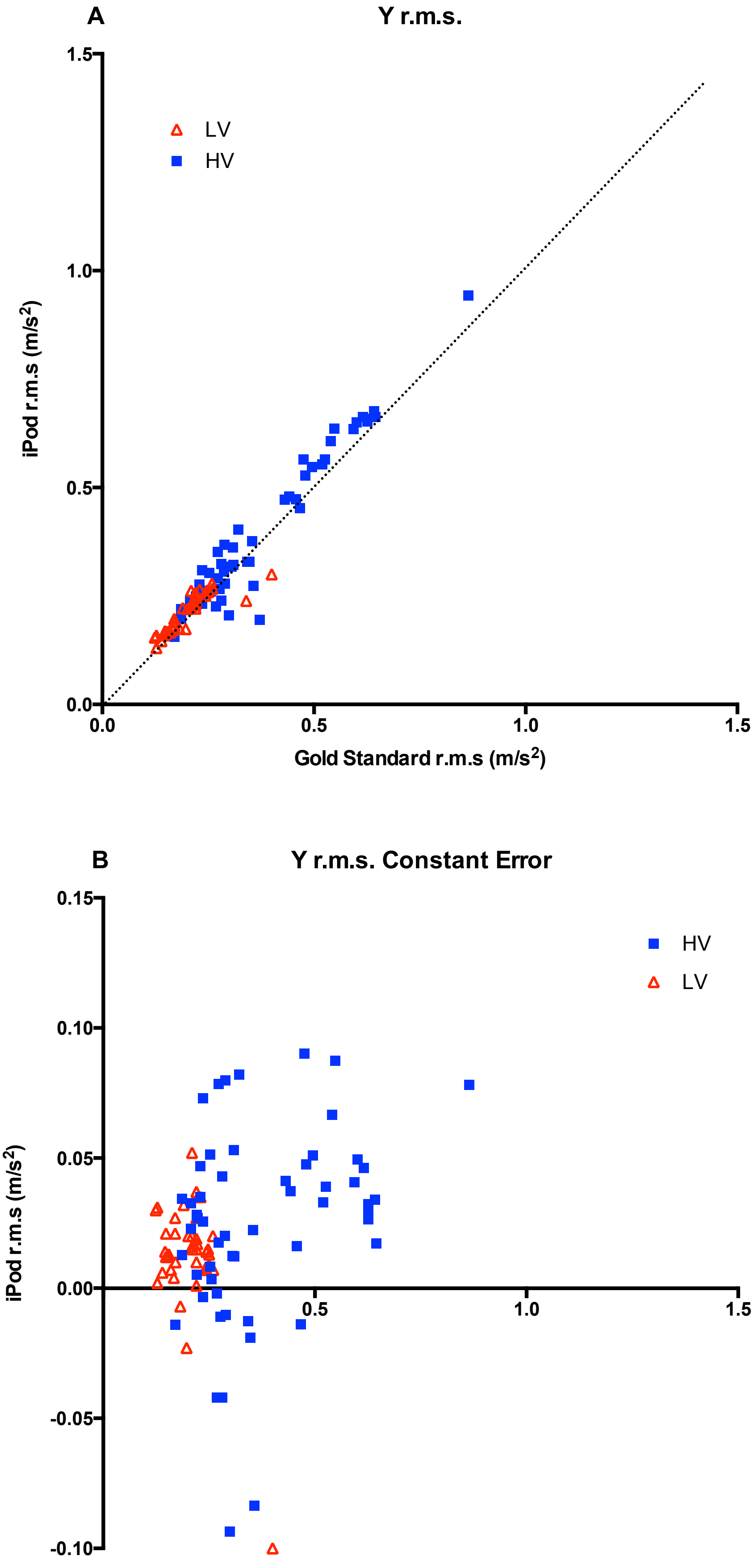


Figure 12: Y direction (side-to-side) accelerations (r.m.s) for heavy and light vehicles. Upper panel (A) presents iPod measured data as a function of gold standard measured values. Lower panel (B) presents constant error as a function of gold standard measured values.

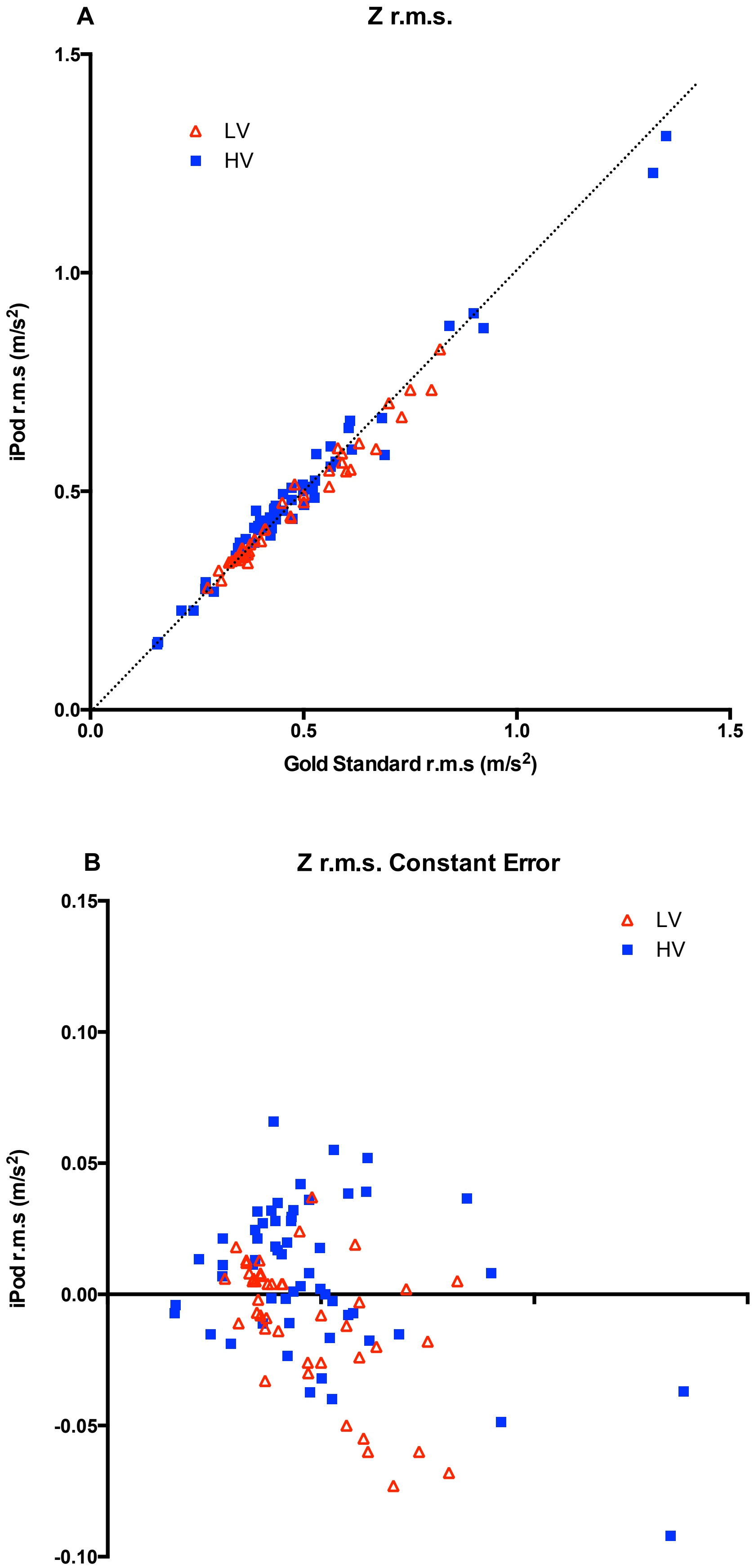


Figure 13: Z direction (vertical) accelerations (r.m.s) for heavy and light vehicles. Upper panel (A) presents iPod measured data as a function of gold standard measured values. Lower panel (B) presents constant error as a function of gold standard measured values.

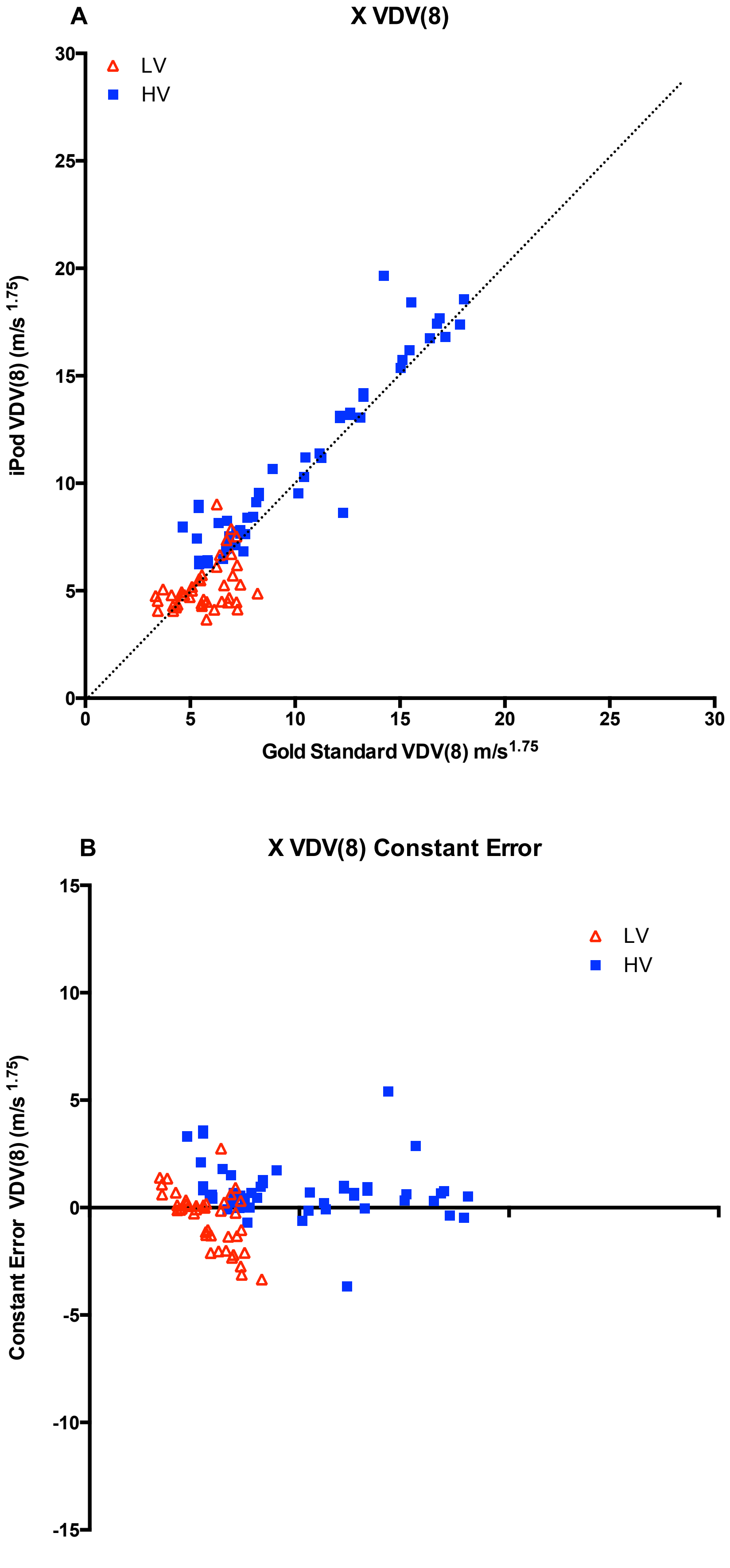
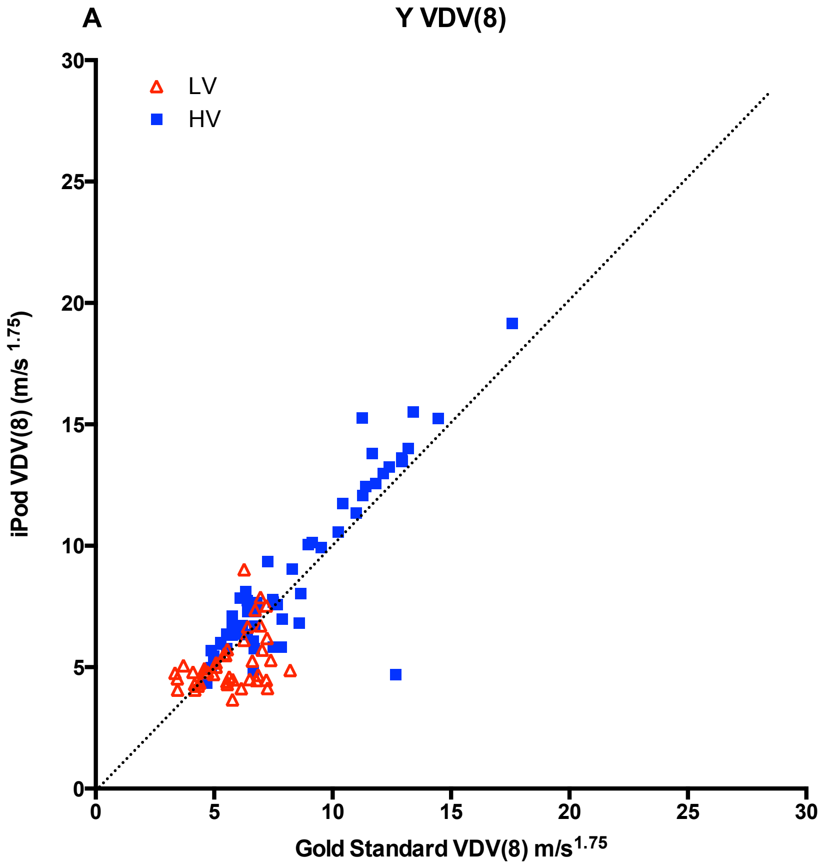


Figure 14: X direction (fore-aft) acceleration VDV(8) for heavy and light vehicles. Upper panel (A) presents iPod measured value as a function of gold standard measured values. Lower panel (B) presents constant error as a function of gold standard measured values.



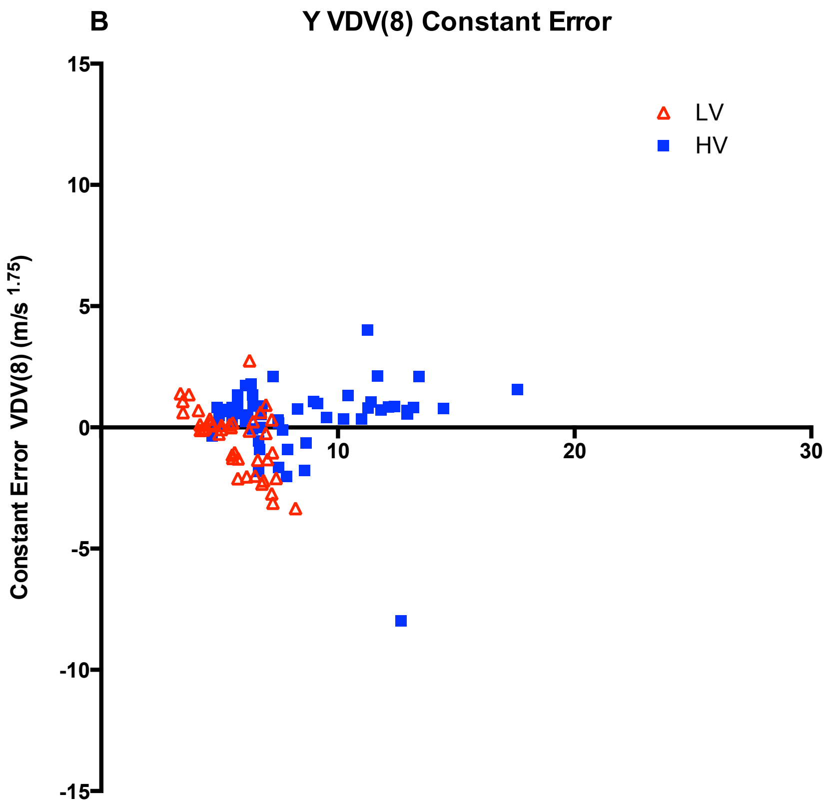


Figure 15: Y direction (side-to-side) acceleration VDV(8) for heavy and light vehicles. Upper panel (A) presents iPod measured value as a function of gold standard measured values. Lower panel (B) presents constant error as a function of gold standard measured values.

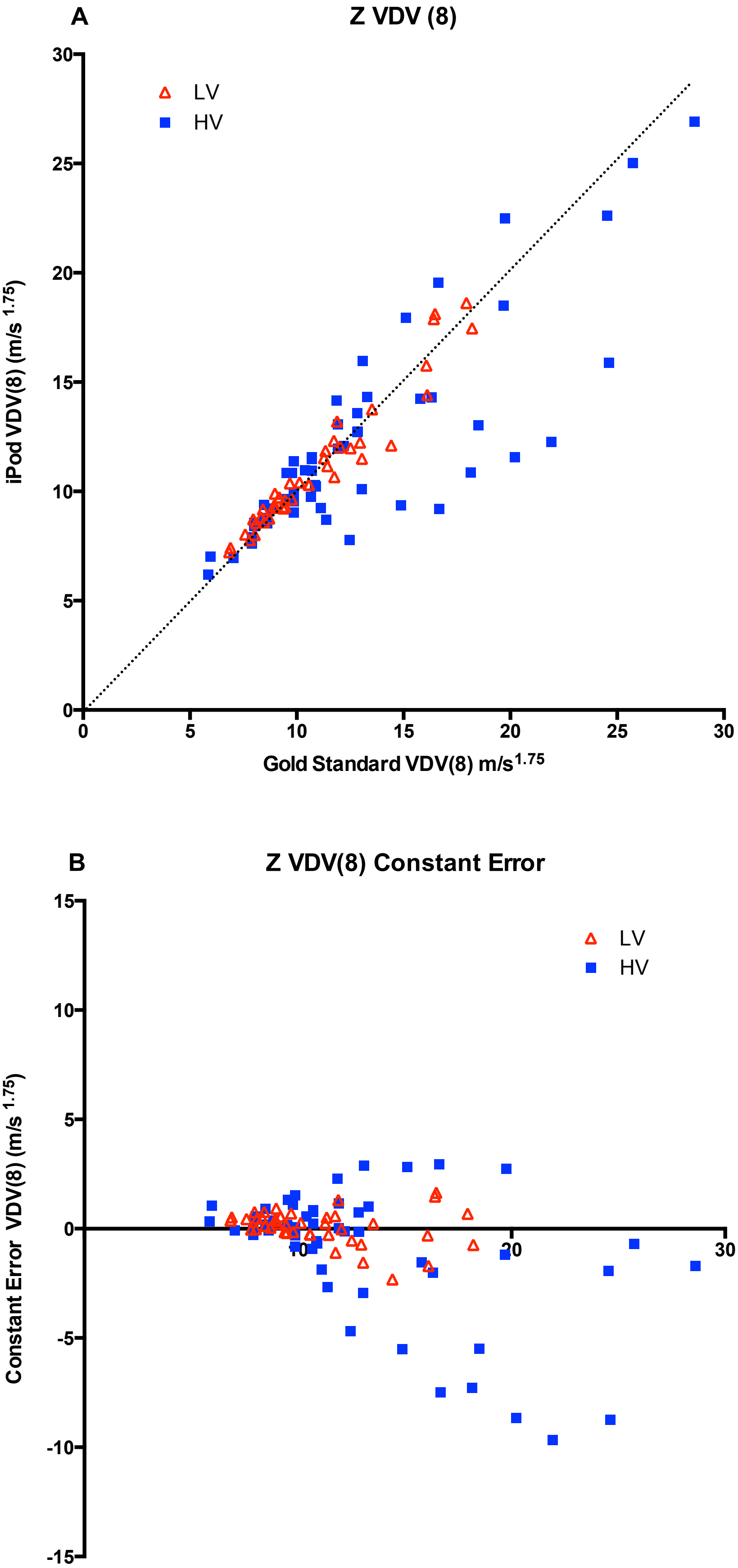


Figure 16: Z direction (vertical) acceleration VDV(8) for heavy and light vehicles. Upper panel (A) presents iPod measured value as a function of gold standard measured values. Lower panel (B) presents constant error as a function of gold standard measured values.

Figure 17 present linear regression equations fitted to r.m.s and VDV(8) constant error for the X, Y and Z directions for 58 pairs of measurements obtained from surface coal mining equipment. The mean constant error, standard deviation (SD) of the constant error, and 95% limits of agreement for the heavy vehicle data are provided in Table 1.

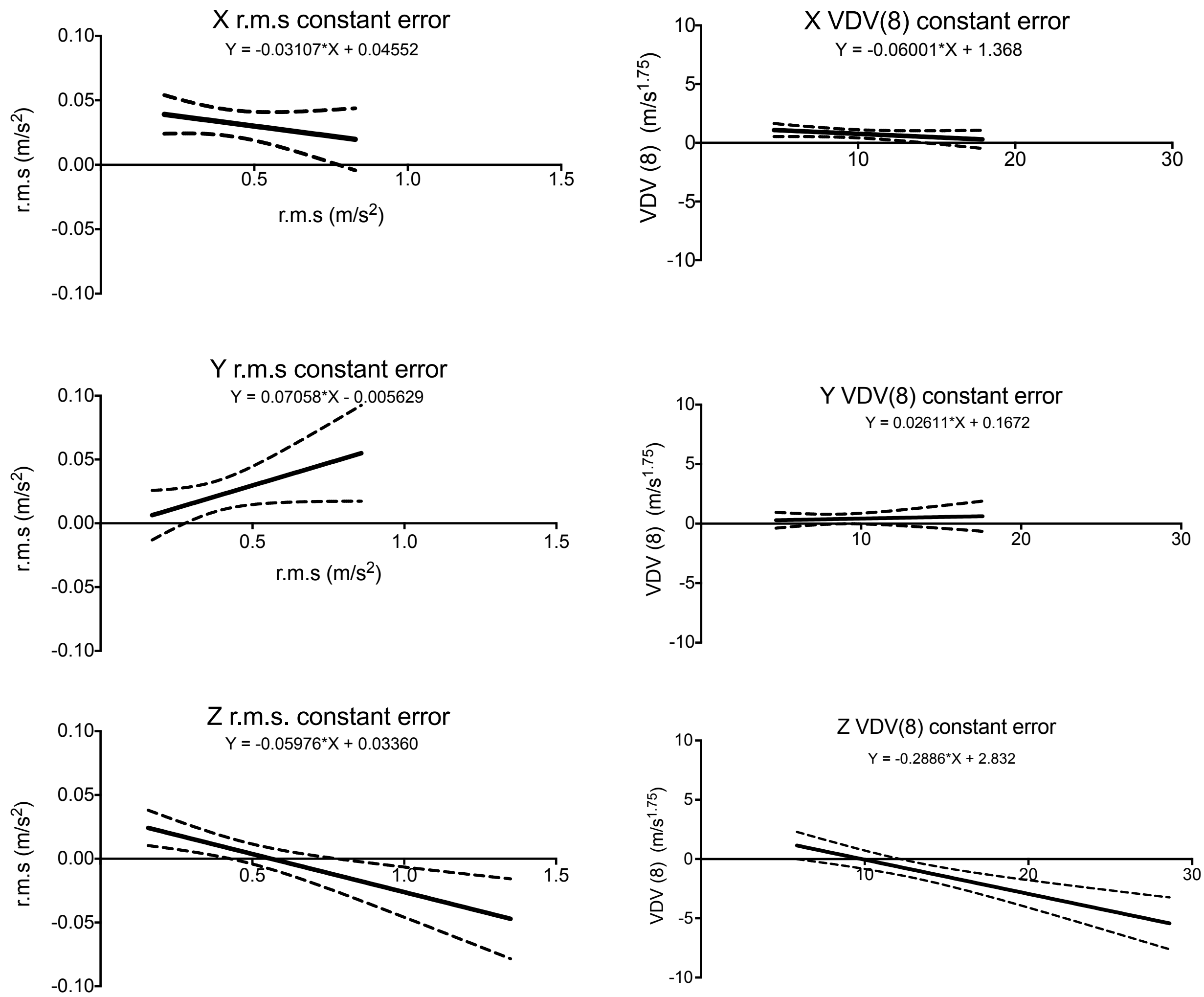


Figure 17: Linear regression equations (and 95% confidence intervals) for 58 pairs of r.m.s and VDV(8) whole body vibration measurements in X, Y and Z directions obtained from three surface mine sites.

Table 1: Mean constant error, standard deviation of the constant error, and 95% limits of agreement (mean +/- 1.96 x SD) for heavy vehicle data gathered from three surface coal mines.

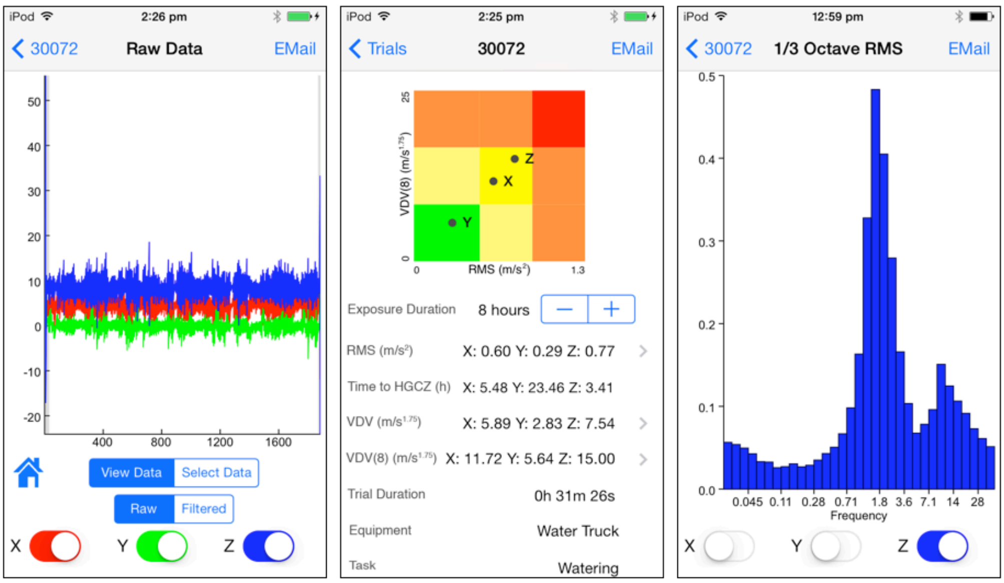
	X r.m.s. m/s^2	Y r.m.s. m/s^2	Z r.m.s. m/s^2	X VDV(8) $m/s^{1.75}$	Y VDV(8) $m/s^{1.75}$	Z VDV(8) $m/s^{1.75}$
Mean constant error	0.032	0.021	0.005	0.802	0.392	-0.882
Standard deviation of constant error	0.038	0.046	0.032	1.295	1.523	2.894
Lower 95% limit of agreement	-0.042	-0.069	-0.058	-1.736	-2.594	-6.55
Upper 95% limit of agreement	0.107	0.110	0.068	3.340	3.378	4.790

The data presented above derived from light vehicles driving over diverse roadways, and diverse heavy vehicles in operation at three surface coal mines, provide an indication of the accuracy limitations of accelerometer data obtained via an iPod Touch for estimating whole body vibration exposure. While the regression equations indicate that the constant error may vary systematically as a function of the acceleration magnitudes, the data indicate that r.m.s. values calculated from data obtained via the iPod Touch are likely (with 95% confidence) to be within 0.06 m/s^2 of the value measured by a gold standard device and VDV(8) values measured by iPod Touch are likely to lie within 6 $m/s^{1.75}$ of the gold standard measured value.

These data confirm that the accelerometer data obtained via an iPod has potential to provide a sufficiently accurate measure of whole body vibration exposure to be useful in identifying and evaluating control measures for reducing whole body vibration exposure at surface coal mines. A paper describing the results of the laboratory and light vehicle testing of the prototype application has been published in the *Journal of Occupational and Environmental Hygiene*[20]; and a paper describing the heavy vehicle data has been published in the *Annals of Occupational Hygiene*[21].

WBV iOS application

An iOS application (WBV) was developed in conjunction with Byteworks (www.byteworks.us). The application allows the collection of three-dimensional accelerometer data while an iPod Touch is placed on the seat of a vehicle or mobile plant in operation. The battery life allows collection periods up to approximately 8 hours. At the conclusion of a trial the Wd and Wk frequency weightings are applied to the raw accelerometer data as specified by ISO2631.1. The data which have been collected can then be inspected as a time series to identify any potential artefacts, and if necessary, data from the start and/or end of the trial may be non-destructively excluded from subsequent calculations (Figure 18a). A global setting also allows a fixed period of up to 10s to be cropped from the start and end of each trial by default.



(a) (b) (c)

Figure 18: WBV application screens (a) time series data for visual inspection; (b) numerical and graphical presentation of summary statistics relative to the ISO2631.1 health guidance caution zone for the nominated exposure duration; and (c) frequency spectrum of collected acceleration data.

The application calculates r.m.s, Vibration Dose Value (VDV), and VDV(h) measures, (where h is the hours of exposure to the task each shift nominated by the user). These measures are presented numerically, and graphically with respect to the ISO2631.1 health guidance caution zone (HGCZ) appropriate for the nominated shift duration (Figure 18b). The frequency spectrum of the accelerometer data may also be calculated and displayed (Figure 18c). The numerical and graphical results, and raw and frequency weighted data, may be subsequently emailed or downloaded for reporting or further analysis. The application, user manual (Appendix A), and training materials are available for free download via the project website (ergonomics.uq.edu.au/wbv).

Additional validity and usability testing has been undertaken at a central Queensland coal mine, including the successful use of the application on 30 iPods to collect 61 samples of "whole-shift" data from nine equipment types over three days.

Conclusion

The relatively low cost of the iPod Touch hardware, and simplicity of the WBV application, has the potential to facilitate routine collection of whole-body vibration exposure by site-based workplace safety and health staff as part of a systematic whole-body vibration risk management program. The ability to respond rapidly to operator feedback or complaints may also allow early identification of developing problems with roadways or equipment.

It is feasible for multiple iPod Touch devices to be used to collect whole shift vibration data for all equipment on site in conjunction with other variables such as road condition, weather, task, location and speed. The availability of the WBV application facilitates collection of adequate data to allow the identification and understanding of the sources of uncertainty in the evaluation of occupational exposure to whole-body vibration.

As well as allowing valid assessments of health risks to be undertaken at a workplace, identifying the combinations of factors which lead to elevated vibration amplitudes provides valuable insight into the potential means of implementing effective risk control interventions. The ability to easily collect whole-body vibration data allows the potential effectiveness of suggested control measures to be assessed as part of the risk management process. In sum, the iOS application has potential to effectively evaluate whole-body vibration exposure within a workplace risk management process.

References

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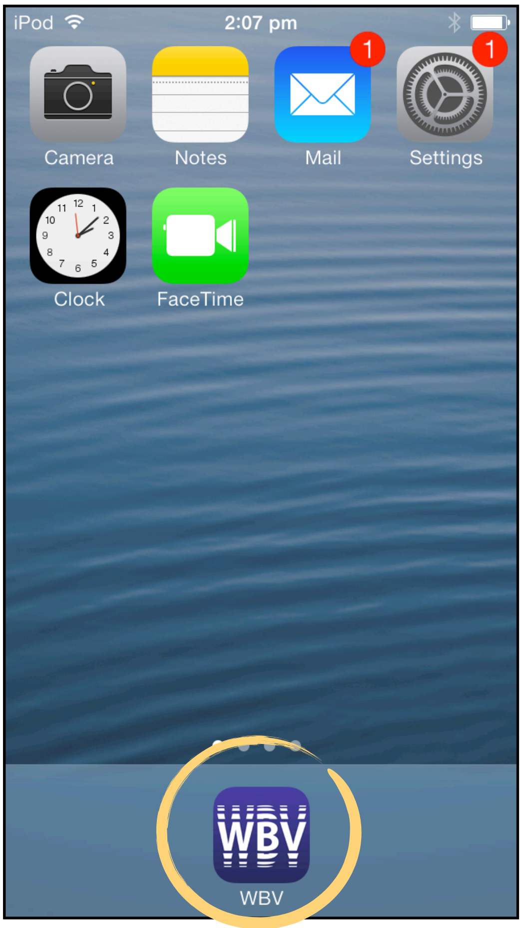
Appendix A - WBV v2.2 user manual

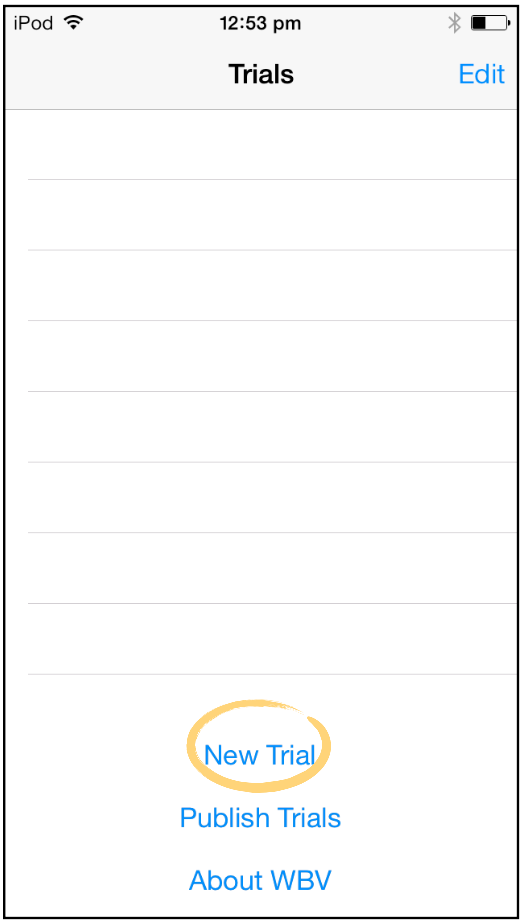


The WBV application captures accelerometer data and calculates frequency weighted estimates of whole-body vibration amplitude according to the methods outlined in ISO2631.1

The WBV application has been tested for use on a 5th generation iPod Touch running OS7, although will run on other devices, and in OS6.

The results produced by the application in conjunction with a 5th generation iPod Touch are believed to be consistent with those produced by gold standard whole-body vibration measurement devices, although no warranty is made. See additional technical information available at the WBV website for more information.

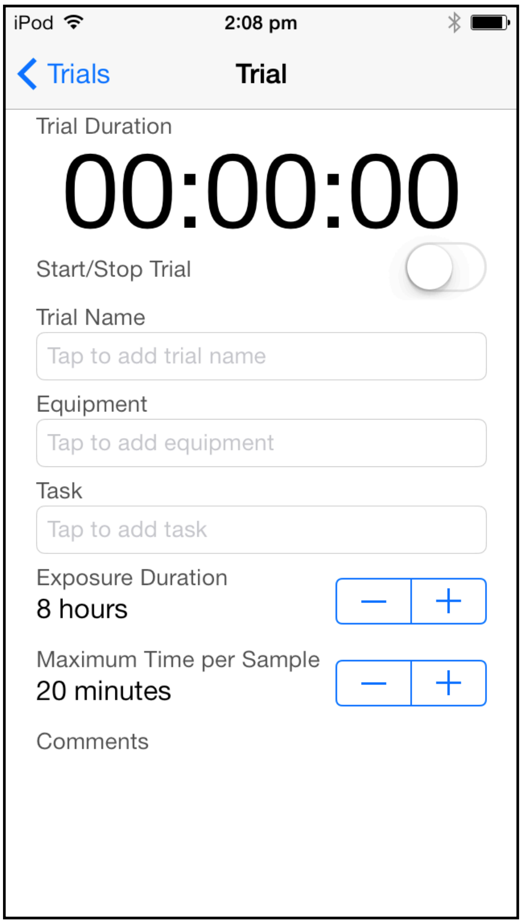
To launch, select the WBV icon



The “Trials” screen is initially empty.

Select “New Trial”.

Appendix A - WBV v2.2 user manual

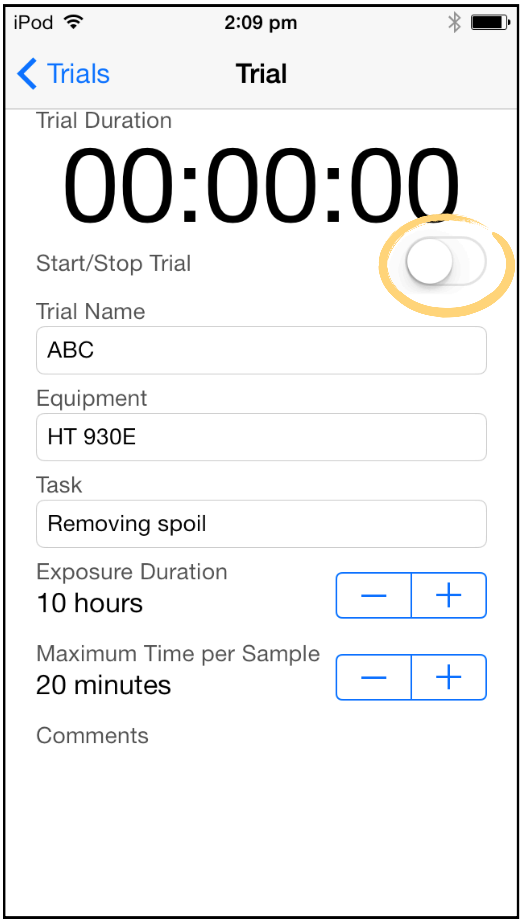


Enter a trial identifier (Trial name). Equipment and Task details are optional.

Typical exposure duration may be nominated or left as the default. This can be altered later and the results will be recalculated.

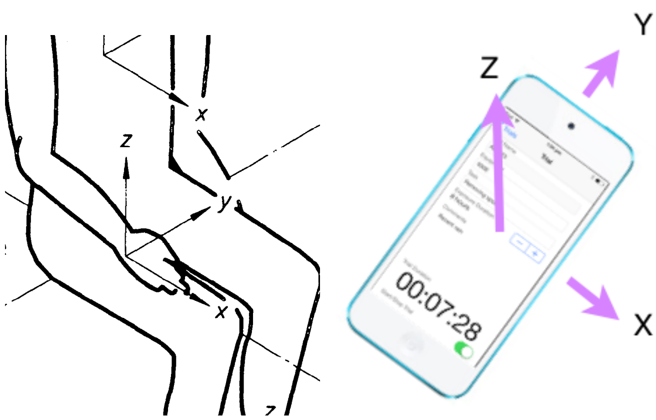
If the maximum time per sample is left at “no limit, the file starts and stops when the trial is started and stopped. If the maximum time per sample has any other value, and the total trial duration exceeds this value, then multiple files are created - effectively “chunking” the trial into sub-samples.

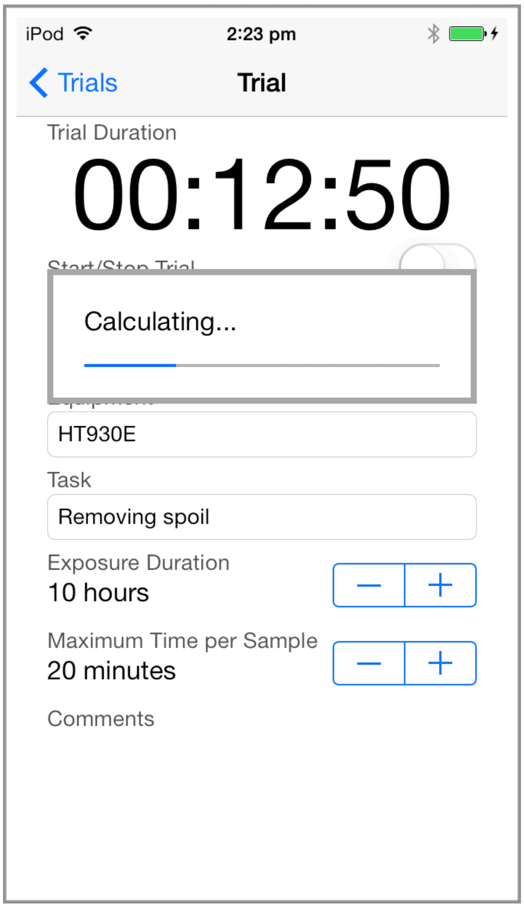
Comments about the trial can be added here or added and edited subsequently.



Tap Start/Stop button to initiate sampling.

Place iPod Touch face down on the seat under the equipment operator’s left or right ischial tuberosity, with the long axis of the iPod perpendicular to the direction of travel.

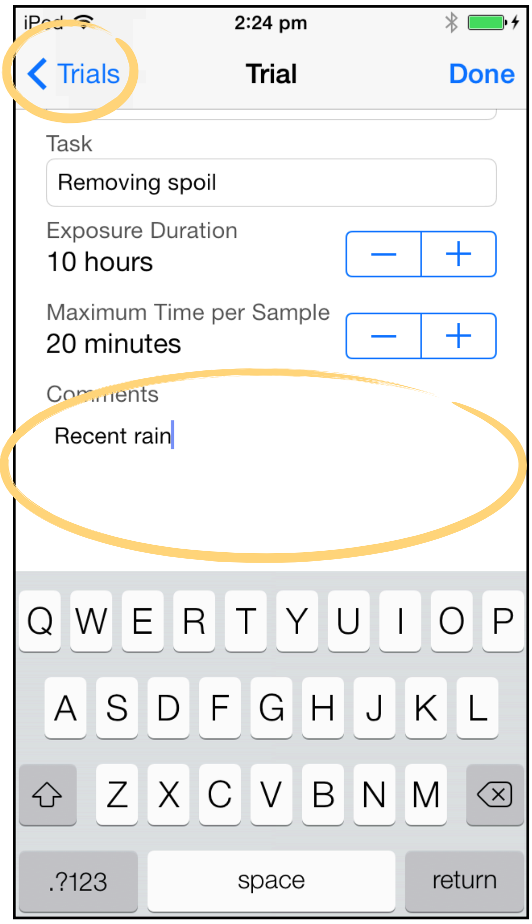




Tap Start/Stop button to stop sampling.

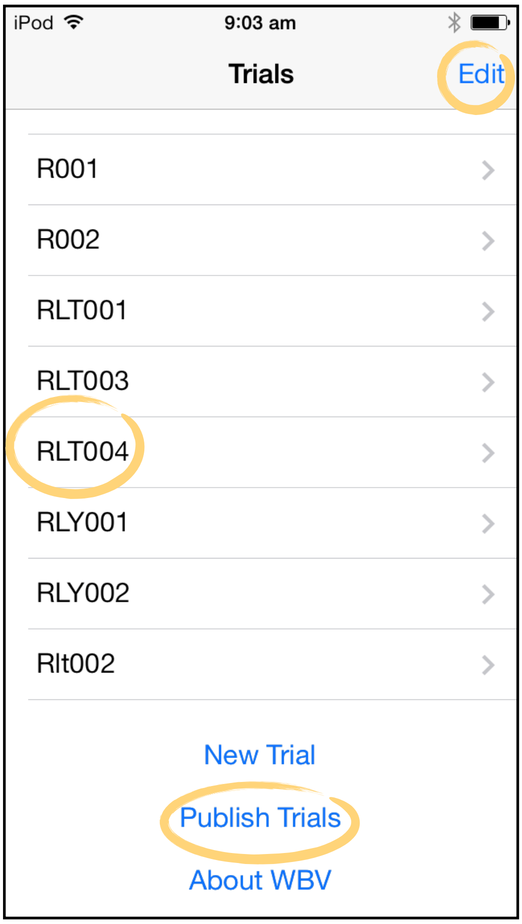
By default, the first and last 10s of data are excluded from the subsequent calculations to avoid motion artifacts. This is able to be altered in the system settings.

"Calculating" appears while the acceleration data are frequency weighted according to ISO2631.1, followed by calculation of r.m.s. and Vibration Dose Values with respect to the Health Guidance Caution Zone



Tap comments text box to add or edit Comments.

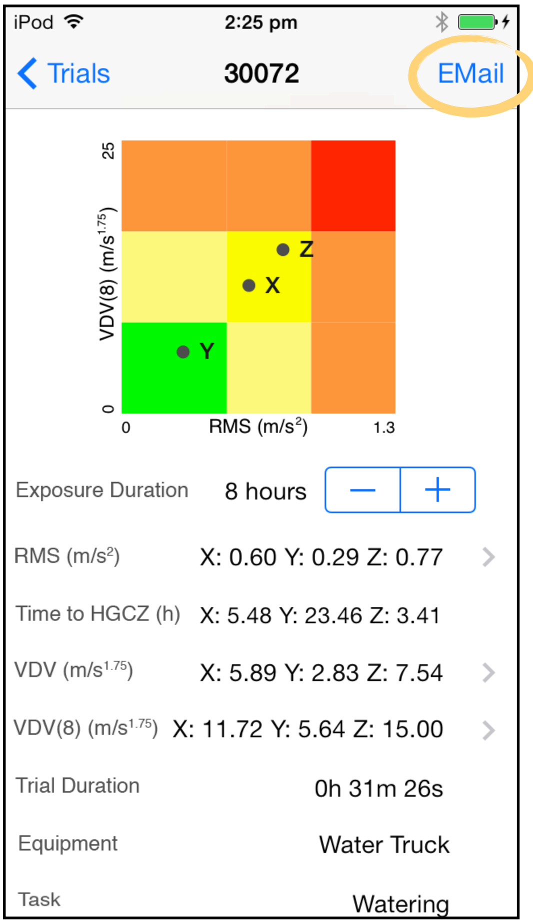
Select "Trials" to return to the trials screen.



Select trial name to inspect and email single trial results.

Select "Edit" to delete trials

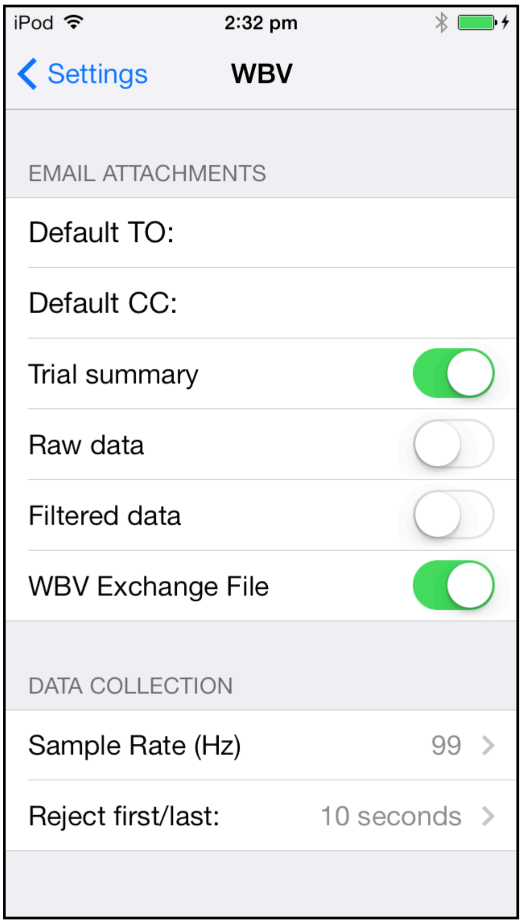
Select "Publish Trials" to download via wireless network.



The results screen for each trial provides a graphical presentation of the frequency weighted X, Y and Z direction vibration amplitude expressed as RMS and Vibration Dose Value relative with the ISO2631.1 Health Guidance Caution Zone. VDV is a cumulative measure and is consequently described as the VDV for the sample duration, and as VDV(n) where n is the exposure duration selected (1, 2, 4, 8, 10 or 12 hours). The time to reach the RMS HGCZ is also calculated.

Increasing or decreasing the typical exposure duration selected causes VDV(n) to be re-calculated. The boundaries of the HGCZ are also altered for RMS according to the exposure duration selected.

Select "EMail" to email the results of a single trial. By default the results graphic and text are included. A csv file of the results and raw and filtered accelerometer time series can also be attached. A file which can be imported to WBV on another iOS devices can also be emailed. This behaviour is determined in the WBV panel of the general settings.

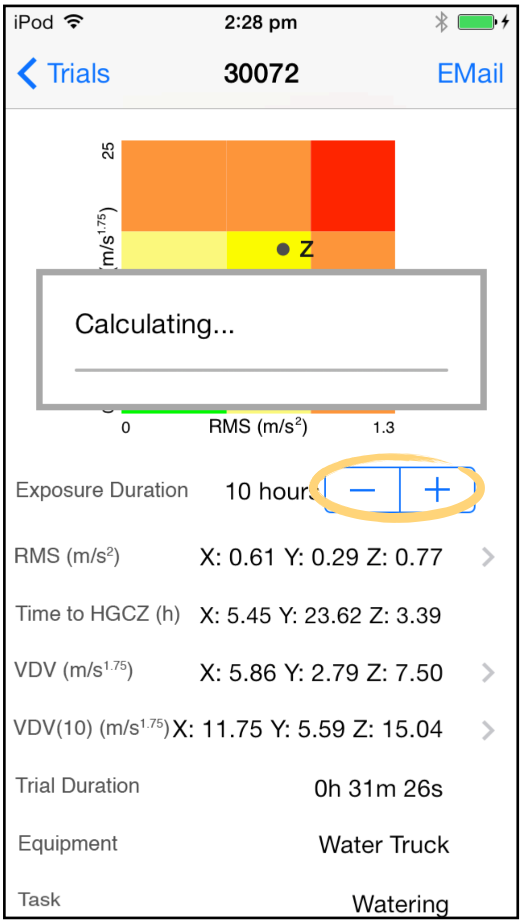


From the iPod Touch “Settings” control panel, select WBV.

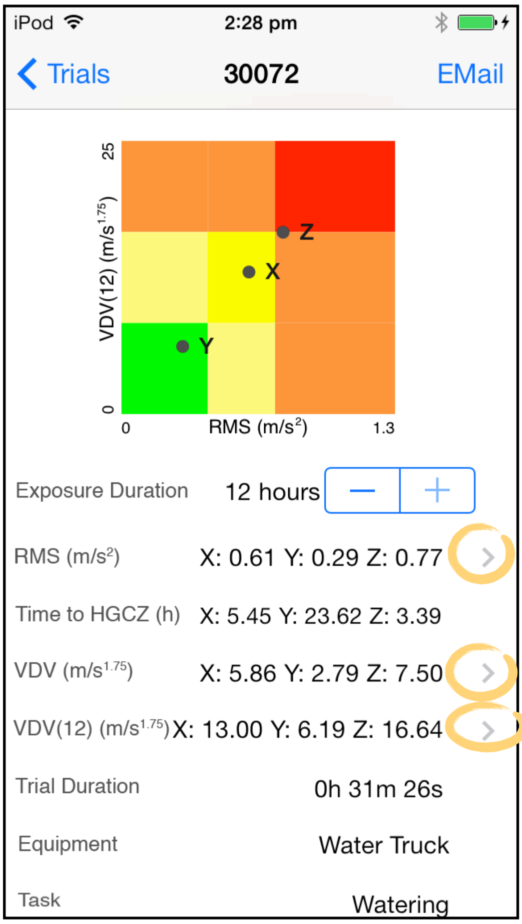
Email attachment behaviour, nominal sampling rate, and the duration of data to be ignored at the start and end of each trial is adjusted here.

NB: Selecting a nominal sampling rate of 100 Hz is not recommended because it appears to result in a bimodal distribution of inter-sample intervals.

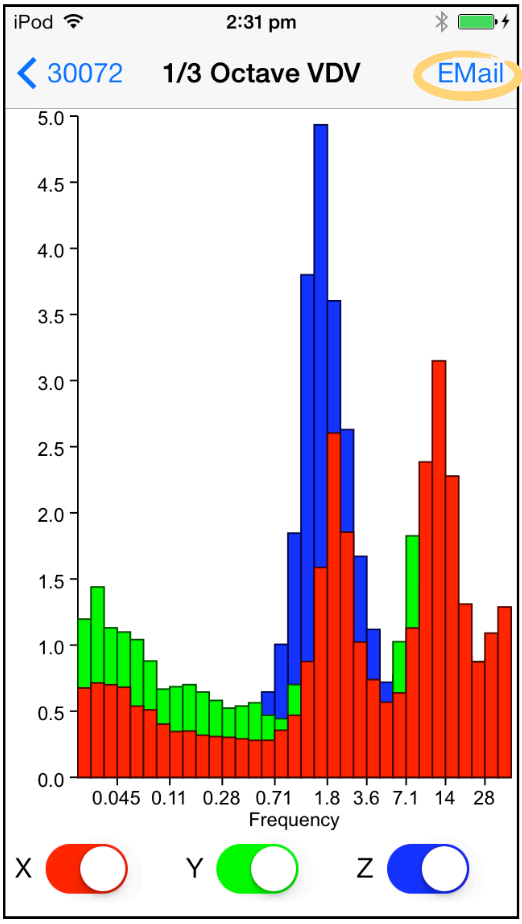
The actual sampling rate achieved varies (and is reported for each trial in the trial results).



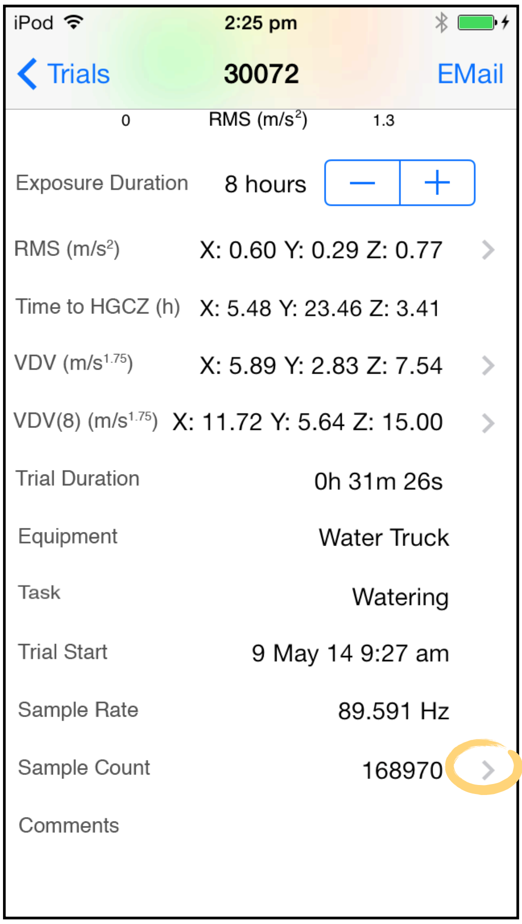
Altering the nominated exposure duration causes the results to be recalculated.



Selecting the arrow adjacent to the RMS or VDV result calls up frequency spectra calculated for the sample.

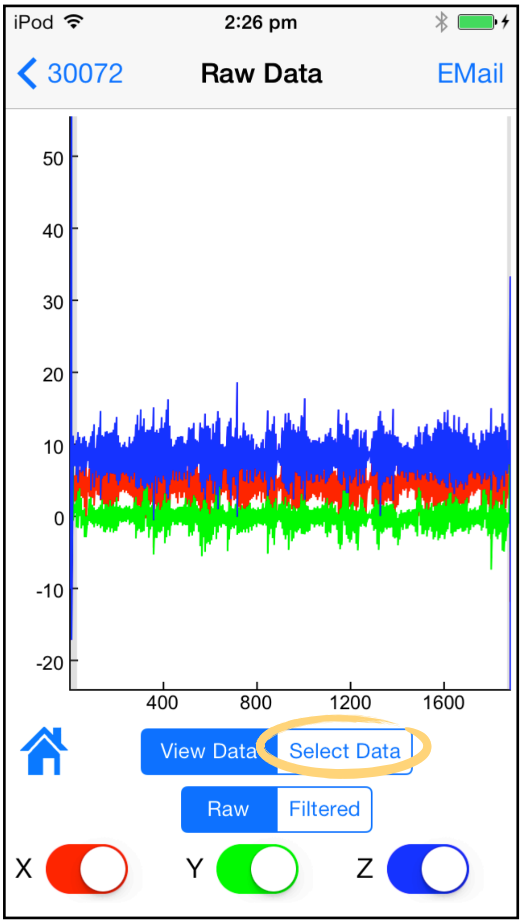


The frequency spectra figure and data can be emailed from this screen.

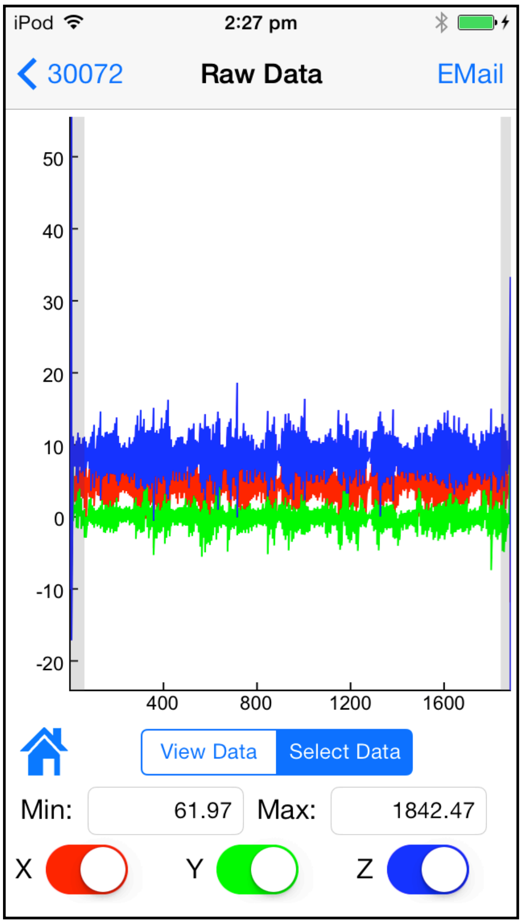


Scrolling down the results screen reveals additional information about the trial.

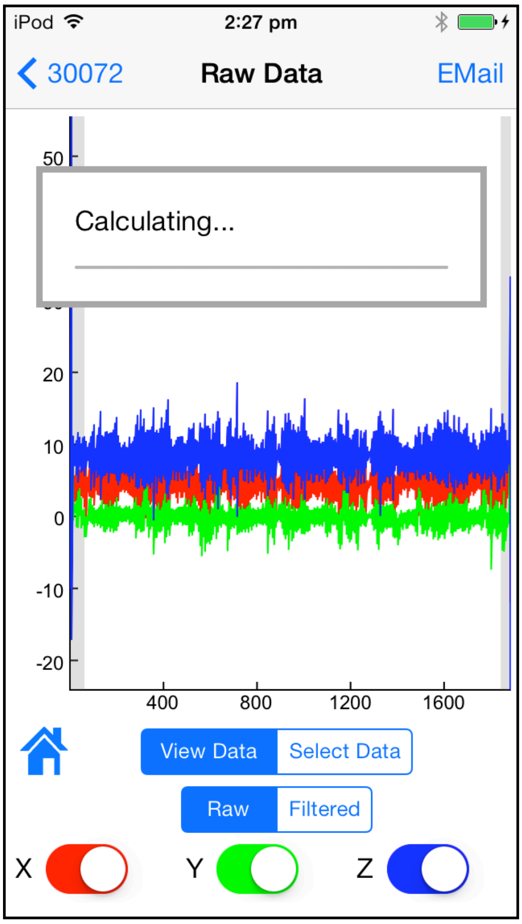
Selecting the arrow adjacent to the sample count reveals the raw and filtered data.



The raw and filtered data may be inspected, particularly for movement artifacts.



Select Data may be used to crop any movement artifacts, either by swiping the Min and Max time (shaded region), or entering these times directly.



Selecting View Data causes all results to be recalculated using the selected data.