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Laboratory and field measurements and evaluations of vibration at the handles of riveting hammers

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Abstract

The use of riveting hammers can expose workers to harmful levels of hand-transmitted vibration (HTV). As a part of efforts to reduce HTV exposures through tool selection, the primary objective of this study was to evaluate the applicability of a standardized laboratory-based riveting hammer assessment protocol for screening riveting hammers. The second objective was to characterize the vibration emissions of reduced vibration riveting hammers and to make approximations of the HTV exposures of workers operating these tools in actual work tasks. Eight pneumatic riveting hammers were selected for the study. They were first assessed in a laboratory using the standardized method for measuring vibration emissions at the tool handle. The tools were then further assessed under actual working conditions during three aircraft sheet metal riveting tasks. Although the average vibration magnitudes of the riveting hammers measured in the laboratory test were considerably different from those measured in the field study, the rank orders of the tools determined via these tests were fairly consistent, especially for the lower vibration tools. This study identified four tools that consistently exhibited lower frequency-weighted and unweighted accelerations in both the laboratory and workplace evaluations. These observations suggest that the standardized riveting hammer test is acceptable for identifying tools that could be expected to exhibit lower vibrations in workplace environments. However, the large differences between the accelerations measured in the laboratory and field suggest that the standardized laboratory-based tool assessment is not suitable for estimating workplace riveting hammer HTV exposures. Based on the frequency-weighted accelerations measured at the tool handles during the three work tasks, the sheet metal mechanics assigned to these tasks at the studied workplace are unlikely to exceed the daily vibration exposure action value (2.5 m s^{-2}) using any of the evaluated riveting hammers.

Keywords

exposure estimation; HAVS; musculoskeletal injury; risk assessment; vibration

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INTRODUCTION

Riveting hammers paired with bucking bars are widely used in the construction and maintenance of aircraft, ships, land vehicles, and in other construction and manufacturing settings. Some riveting hammer models can generate very high transient or impulsive vibrations (Dandanell and Engstrom, 1986), which can be effectively transmitted to the fingers or hand from the riveting hammers themselves and through the bucking bars (Kattel and Fernandez, 1999). The resulting hand-transmitted vibration (HTV) could lead to instances of hand-arm vibration syndrome (Yu *et al.*, 1986; Burdorf and Monster, 1991; McKenna *et al.*, 1993). It has been estimated that in some work environments, >50% of riveters could exhibit symptoms of vibration-induced white finger (a major component of the hand-arm vibration syndrome) after 10 years of work (Engstrom and Dandanell, 1986). Moreover, the riveting process usually requires forceful exertions and repetitive actions. In some cases, the process may also require awkward hand and finger postures, especially while gripping the bucking bar. Other consequences associated with HTV exposures are increases in the gripping forces and cycle times required for completing the riveting tasks (Fredericks and Fernandez, 1999), which may account for increased incidence of carpal tunnel syndrome and other hand and wrist musculoskeletal disorders among riveters (Burdorf and Monster, 1991; NIOSH, 1997). Therefore, it is very important to control HTV exposures to rivet workers.

To help control HTV exposures, the International Organization for Standardization (ISO) has set forth a standard for the measurement, evaluation, and assessment of HTV exposures (ISO 5349-1, 2001a). While this international standard does not establish HTV exposure limits, many countries have recommended or specified a daily exposure action value (DEAV) and a daily exposure limit value (DELV) in their National Standards or Directives on human vibration exposure (EU, 2002; ANSI S2.70, 2006). According to these publications, employers are suggested or required to take actions to reduce HTV exposures if they exceed the DEAV. They further state that no worker should be exposed to HTV above the DELV. Although exposure controls may not eliminate all instances of hand-arm vibration syndrome and other disorders, it is anticipated that effective exposure control strategies can help minimize harm.

One of the positive effects of the standards and directives is that they have encouraged employers to provide safer powered hand tools for their workers. Employers and tool users are initiating programs to replace old tools with improved models. In turn, tool developers have responded to this demand through increased efforts to develop reduced vibration tools such as riveting hammers (Peng, 1994; Cherng *et al.*, 2009). To help buyers evaluate and select lower vibration tools, the ISO developed a series of laboratory-based testing standards for comparing tools according to their tool handle vibration emissions (ISO 8662-1, 1992a). Part 2 of this series (ISO 8662-2, 1992b) pertains specifically to chipping hammers and riveting hammers. While this original standard requires measuring the vibration emission from the handle of each riveter in only the dominant axis, its updated version requires measuring the vibrations in three orthogonal directions (ISO 28927-10, 2011). A few alternative tool vibration evaluation methods with some minor differences from the ISO standardized method are also available (e.g., PNEUROP, 2005).

The vibration emission values declared by tool manufacturers are usually based on measurements made in accordance with the ISO standardized method. Tool selections can be, at least partially, based on these declared values as long as the measurements are directly comparable. This may largely depend on the reliability and consistency of the data measured at different laboratories or in different test series. Further studies are required to evaluate the reliability and consistency of these values.

Another major concern is that the vibration levels measured in laboratory-based tests could be substantially different from workplace exposures. This means that laboratory test results should not be directly used for evaluating actual workplace HTV exposures. However, if tools can be rank ordered in terms of vibration magnitude, and laboratory-based rank orders would be the same or similar to workplace rank orders, it may be appropriate to use laboratory-based test results to make preliminary tool selections or to help judge whether or not a new tool design is superior to existing tools. Further studies are required to test this hypothesis.

Moreover, the vibration magnitude is only one of two factors that determine the daily exposure dose required to examine compliance with the DEAV and DELV. The other factor is the daily vibration exposure duration. It is possible that exposure durations could increase if the selected reduced vibration tool increases the time required to perform the work task. Therefore, the tool selection process should also include workplace evaluations of the selected tools. Workplace tool assessment results can be compared with laboratory-based results or to manufacturer-declared vibration emission values. The workplace evaluations can also include examinations of compliance with other safety and ergonomic criteria. Worker preferences may also be discerned in the assessments. Further, judgments of status regarding the DEAV and DELV can be based on measurements conducted in accordance with the methods defined in ANSI S2.70 (2006) or ISO 5349-1 (2001a).

As mentioned above, even if HTV exposures are controlled to levels below the DEAV, incidences of vibration-induced disorders may not be completely eliminated. This may be partially due to inappropriate frequency weighting prescribed by the current standards for evaluating HTV exposures; evidence exists that the application of the current frequency weighting may not be suitable for high-frequency or impulsive vibration exposures (Dandanell and Engstrom, 1986; Nilsson *et al.*, 1989; Starck *et al.*, 1990). While frequency weighting remains a major research issue (Pelmear *et al.*, 1989; Wasserman, 1989; Bovenzi, 1998), the results of some reported studies suggest that unweighted acceleration may be used as an additional measure to assess HTV exposures (NIOSH, 1989; Griffin *et al.*, 2003). Such a practice is also supported by recent research; vibration accelerations weighted with recently proposed finger biodynamic frequency weighting (Dong *et al.*, 2008; Dong, 2011) or frequency weighting derived from epidemiological data of vibration-induced white finger (Tominaga, 2005) are highly correlated with unweighted accelerations of powered hand tools (Dong *et al.*, 2008; Pitts *et al.*, 2011). However, it is unknown how riveting hammer selections based on unweighted acceleration compare with those based on ISO frequency-weighted acceleration.

The United States Air Force (USAF) 72nd Aerospace Medicine Squadron (72 AMDS) at Tinker Air Force Base (AFB) in Oklahoma has identified sheet metal mechanics as having a high risk of experiencing upper extremity ergonomic illnesses. It is presumed that a major ergonomic stressor for these sheet metal mechanics is HTV from powered hand tools, especially during riveting operations. In keeping with the U.S. Occupational Safety and Health Act of 1970, Section 5, General Duty Clause (OSHA, 2002) and the aforementioned ANSI standard (ANSI S2.70, 2006), the 72 AMDS is interested in learning more about the vibration levels of riveting hammers used by their sheet metal mechanics, protecting those workers against potentially harmful HTV exposures, and in developing means to improve the process it uses in selecting hand-held power tools for workers at Tinker AFB. This provided a good opportunity for us to address some of the above-mentioned issues and to test the related hypotheses.

Specifically, the primary objective of this study was to evaluate the applicability of a standardized laboratory-based riveting hammer assessment protocol for screening riveting hammers. The secondary objective was to characterize the vibration emissions of reduced vibration riveting hammers and to approximate daily HTV exposures for workers using these tools during selected riveting tasks at Tinker AFB. Some other implications of the study results are also discussed.

METHODS

The study was completed in two phases; the first part (laboratory study) was conducted at the NIOSH hand-arm vibration laboratory in Morgantown, WV, while the second part (field study) was completed at Tinker AFB, Oklahoma.

Laboratory data collection

Six male riveting hammer operators were recruited from a pool of local workers to participate in the laboratory portion of the study. While all the study participants were experienced tool operators, none of them were familiar with the riveting tasks conducted at Tinker AFB. The tool operators participated in the experiment on a paid and informed consent basis. The tool operators followed a protocol that was reviewed and approved by the NIOSH Human Subjects Review Board.

The USAF purchased eight new pneumatic riveting hammers for the assessment. Each of the tool models selected by USAF 72 AMDS was described as a ‘reduced vibration’ model. Details of the eight tools are listed in Table 1. Prior to the laboratory assessment, each of the tools was lubricated and ‘broken in’ in accordance with the specifications provided by the tool manufacturers.

The percussive tool laboratory test setup used in this study was designed and constructed based on the requirements of the ISO standard for the measurement of vibrations at the handles of chipping hammers and riveting hammers (ISO 8662-2, 1992b). (As noted above, an updated version of this ISO standard has since been published as ISO 28927-10, 2011.) The test apparatus with one of the tested tools (Tool D1) is shown in Fig. 1. The key feature of the test apparatus is the energy absorber. In accordance with the ISO standard, the energy absorber is comprised of a steel tube filled with hardened steel balls. The absorber is firmly mounted on a rigid steel base that is secured to a concrete block. A cap and bushing assembly is affixed to the top of the steel cylinder to prevent the escape of any of the steel balls and to trap any fragments in the unlikely event of bit failure. When the percussive tool operates, the energy absorber provides a dynamic reaction force that enables stable and reproducible tool action.

At the beginning of this study, the eight tools were equipped with identical, brand-new, hardened steel riveting bits (5/8″ × 7-1/2″). None of the eight bits were changed during the course of the study. A hardened steel disc rests on top of the column of steel balls inside the energy absorber. Prior to a set of five trials for a tool, its bit was inserted into the top of the energy absorber so that the tip of the bit rested on the center of the hardened steel disc.

The tools were evaluated by measuring vibrations near the midpoint of the tool handle in the finger contact area, as shown in Figs 2 and 3. All tool handle vibration measurements were collected via PCB Model 356B11 piezoelectric triaxial accelerometers. The accelerometers were installed on mounting blocks and secured to the tool handles with hose clamps. The tool accelerometer mounting technique is also shown in Figs 2 and 3. All accelerometers were calibrated prior to the experiment, and when necessary, correction factors were applied to the test data during processing.

The measurement of vibration of percussive tools often yields significant DC shifts in the piezoelectric accelerometer output (Griffin, 1990). Consequently, mechanical filters comprising three layers of synthetic rubber (cut from a bicycle tire inner tube) were used to minimize or eliminate the DC shift. A sample mechanical filter is shown in Fig. 3. This synthetic rubber layering technique has been proven to be successful in several earlier experiments involving impact tools (Dong *et al.*, 2004; McDowell *et al.*, 2008, 2009). The validity of the measurement during each trial was examined by checking the low-frequency (<25 Hz) spectrum (Maeda and Dong, 2004).

Each operator stood on a force measurement plate/platform and applied a downward push force on the tool handle. The platform height was adjusted for each tool operator to help standardize the posture and to maximize comfort. The tool operators assumed the posture described in the ISO standard (ISO 8662-2, 1992b); this posture is depicted in Fig. 4. As required by the standard, the applied feed force should be 40 times the tool weight but should not be <80 N or >200 N. Hence, the tool operators were instructed to apply a feed force of 100 ± 20 N. The force measurement plate (Kistler Type 9286AA) was used to measure the applied feed force. A computer monitor was placed directly in front of the subject, which displayed a full-screen force strip chart so that the tool operator could monitor and control the feed force during tool operation. The operators were also instructed to apply just enough grip force to maintain safe operation of the tool, but the grip forces were not measured during the experiment.

The supplied air pressure was regulated to 620 kPa (90 psi). Each tool’s switch was fixed at the ‘on’ position with electrical tape (see Fig. 2) so that the operator could focus attention on the tool operation and to better facilitate relatively constant feed and grip forces. A test engineer controlled the tool's on/off operation during the test by way of a remote-controlled solenoid valve.

At the beginning of each tool evaluation session, there was a short practice cycle (about 10 min) to allow the tool operator to become familiar with the tool loading task. Following practice, each subject completed five consecutive trials with each tool on the energy absorber for a total of 40 trials in a test session. The testing order of the eight tools was randomized for each tool operator. Each tool test session lasted about 2 hours.

To initiate a trial, the tool operator was instructed to assume the prescribed posture and apply the target feed force. Tool operation and vibration data collection commenced once the test engineer observed the feed force to be stable. The vibration measurement duration was 10 s per trial. At the end of the 10-s data collection period, the tool was stopped by the test engineer, and the tool operator relaxed. The operators rested for about 1 min between trials.

Triaxial acceleration data were collected via a portable six-channel Brüel & Kjær PULSE system featuring Input/Output Module Type 3032A. Both time-history data and frequency spectrum were recorded. The recorded spectra were expressed as the root mean square (rms) values of the accelerations in the 24 one-third octave frequency bands with center frequencies from 6.3 to 1250 Hz. The 'total' values of the rms accelerations were computed using the following formula:

$$a_{h(\mathrm{rms})}=\sqrt{a^2_{hx(\mathrm{rms})}+a^2_{hy(\mathrm{rms})}+a^2_{hz(\mathrm{rms})}}, \quad (1)$$

where $a_{h(\mathrm{rms})}$ is the band-limited unweighted root-sum-of-squares total value, and $a_{hx(\mathrm{rms})}$, $a_{hy(\mathrm{rms})}$, and $a_{hz(\mathrm{rms})}$, are the unweighted rms values for the *x*-, *y*-, and *z*-axis, respectively.

To determine the ISO frequency-weighted acceleration values for each axis, an Excel spreadsheet was used to apply the frequency-weighting factors defined in ISO 5349-1 (2001a):

$$a_{hw(\mathrm{rms})}=\sqrt{\sum_{j=1}^{24}\left(K_j a_{h,j}\right)^2}. \quad (2)$$

where $a_{hw(\mathrm{rms})}$ is the frequency-weighted rms acceleration, K_j is the weighting factor for the *j*th one-third octave band as provided in Table 2 of the standard, and $a_{h,j}$ is the acceleration measured in the *j*th one-third octave band. In this process, the 24 one-third octave frequency band rms accelerations are multiplied by their respective weighting factors, and the resultant weighted rms accelerations are determined for each axis. Then, as was done with the unweighted acceleration, the total ISO frequency-weighted values are computed using

$$a_{hv(\mathrm{rms})}=\sqrt{a^2_{hwx(\mathrm{rms})}+a^2_{hwy(\mathrm{rms})}+a^2_{hwz(\mathrm{rms})}}, \quad (3)$$

where $a_{hv(\mathrm{rms})}$ is the ISO frequency-weighted root-sum-of-squares total value, and $a_{hwx(\mathrm{rms})}$, $a_{hwy(\mathrm{rms})}$, and $a_{hwz(\mathrm{rms})}$ are the ISO frequency-weighted rms values for the *x*-, *y*-, and *z*-axis, respectively.

At the completion of five consecutive trials with a tool, the coefficient of variation (CV) of the ISO frequency-weighted total value ($a_{hv(\mathrm{rms})}$) was immediately calculated for those trials. Trials were repeated if the CV was found to be 0.15 or greater. Vibration measurements proved to be fairly consistent as <5% of all trials required replication.

Tool comparisons were based on ISO frequency-weighted vibration measurements recorded and analyzed in accordance with ISO 8662-2 (1992b). Using this standard method, the eight tools were rank ordered according to the average frequency-weighted tool handle vibration. To provide additional information and to examine how the frequency weighting affects the rank ordering, the tools were also rank ordered by band-limited unweighted tool handle acceleration.

Field data collection

The second phase of the study was conducted at Tinker AFB and consisted of field assessments of the same eight tools that were evaluated in the laboratory. The eight riveting hammers were shipped to Tinker AFB with their accelerometers still installed; thus, accelerometer, mounts, and filters were identical to those used in the laboratory test. The protocol used in the field was based on ISO 5349-1 (2001a) and ANSI S2.70 (2006).

Prior to the field evaluations, all tools were relu-bricated in accordance with each tool manufacturer’s specifications. All tools, accelerometer mounts, and data collection instruments were inspected and operated to ensure proper function and to check for evidence of DC shifts in the acceleration signals.

The 72 AMDS targeted three aircraft maintenance riveting tasks for the field study:

Field Task 1: Riveting skins and ribs for B-52 Side Cowls.

Field Task 2: Riveting skins and ribs for KC-135 Spoilers.

Field Task 3: Riveting skins and ribs for KC-135 Elevators.

Each of the three aircraft riveting workstations are pictured in Fig. 5. In the field portion of the study, the tools were operated by experienced sheet metal mechanics regularly assigned to these specific work tasks at Tinker AFB. Three riveting hammer operators for each of these tasks (a total of nine riveting hammer operators) were selected by 72 AMDS to operate the eight tools. Because the riveting processes for these selected work tasks require bucking bar operators to provide the counter forces necessary to set the rivets, additional sheet metal mechanics were needed to operate bucking bars. However, bucking bar vibration exposures were not evaluated in this study. Figure 6 shows a bucking bar operator providing the counter force during a trial for Field Task 1. For Field Tasks 1 and 2, a single bucking bar operator worked with all three tool operators. Two operators split the bucking bar duties during the riveting tasks for Field Task 3. The field study required 2 days of data collection.

Field Task 1 data were collected on the first day, and Field Tasks 2 and 3 were completed on the second day.

Prior to testing, the three experienced sheet metal mechanics regularly assigned to Field Task 1 along with the bucking bar operator were briefed on the testing procedure. During the evaluation, each of the three operators used each of the eight tools in a predetermined, random order. Over the course of the evaluation, each operator completed three trials with each tool.

Before a set of trials began, a test engineer prepared the designated tool for operation and data collection. The test engineer handed the prepared tool to the tool operator who, along with the bucking bar operator, positioned themselves to complete the first trial. A trial consisted of the complete setting of exactly five rivets within a 30-s span. This rate is within the range of typical production rates for the three field tasks evaluated at Tinker AFB. Unlike the laboratory study, the tool's on/off operation was controlled by the tool operator. At the 'START' command given by the test engineer, the tool and bucking bar operators set five individual rivets in 30 s or less. Data collection commenced at the 'START' command and lasted exactly 30 s. The tool and bucking bar operators used the same riveting techniques (posture, forces, etc.) that are normally employed to complete the task. Once the fifth rivet in the trial was set, the tool and bucking bar operators rested for a few seconds while the test engineer saved the 30-s data file. Once the file was saved, the test engineer prompted the tool and bucking bar operators to get ready for the next trial. This process was repeated until the operators completed three, five-rivet trials. At the end of the third trial, the test engineer checked the data for obvious errors. If timing or other errors were detected, trials were repeated until a full three-trial dataset was collected for that tool/operator combination. Once a three-trial set was complete, the tool operator handed the tool back to the test engineer.

The test engineer then prepared the next tool in the sequence for use by the second tool operator. The process described in the preceding paragraph was then repeated. This process continued until all three tool operators completed three-trial datasets for each of the eight tools.

Once the Field Task 1 data collection was complete, the eight riveting hammers and data collection equipment were relocated to the Field Task 2 work area for a second day of testing. The above-described procedure was then repeated in full with a different set of tool and bucking bar operators. Likewise, once Field Task 2 data collection was complete, the data collection system and tools were moved to the Field Task 3 work area, and the tool operation and data collection procedures were repeated with the third set of tool operators.

As was done in the laboratory study, the tools were rank ordered based on the average ISO frequency-weighted acceleration measurements recorded and analyzed for each of the three field tasks and for the combined average of the three field tasks. As was also done in the laboratory study, the tools were also rank ordered by unweighted tool handle acceleration to provide additional information and to examine the effect of the frequency weighting on the rank orders.

Daily HTV exposure estimates

The ISO-weighted tool handle vibration measurements ($a_{hv(\mathrm{rms})}$) provided in the results section below can be used to estimate HTV exposures associated with the riveting tasks and tools evaluated in this field study. Estimated daily vibration exposure values, A(8), can be calculated using the methods outlined in ISO 5349-2 (2001b) and ANSI S2.70 (2006). The standard equation for estimating A(8) values is

$$A(8)=a_{hv(rms)}\sqrt{\frac{T}{T_0}}, \quad (3)$$

where $A(8)$ is the daily vibration exposure in ms^{-2}, $a_{hv(\mathrm{rms})}$ is the total ISO-weighted vibration magnitude (see equation 3 above), T is the total daily duration of the exposure (in hours), and T_0 is the reference duration of 8 h.

The ISO 5349-2 (2001b) and ANSI S2.70 (2006) standards offer guidance for applying this standard equation to different exposure situations. For the riveting tasks evaluated in this study, the most appropriate method for determining the A(8) values is presented in section E.2.4 of Annex E of ISO 5349-2 (2001b). Briefly, the average frequency-weighted vibration magnitude ($a_{hv(\mathrm{rms})}$) is measured during a controlled number of tool bursts over a fixed duration. Then, the exposure time, T, is determined by dividing the number of bursts per 8-h shift by the number of bursts per evaluation measurement period. In this study, $a_{hv(\mathrm{rms})}$ values represent frequency-weighted vibration magnitude averages of five tool bursts (rivet sets) measured over 30-s periods. Thus, to determine the T values (in min) for the riveting tasks evaluated at Tinker AFB, the following equation should be used:

$$T=(\mathrm{rivets\ per\ 8\text{-}\ h\ shift}\div 5)\times 0.5\,\mathrm{min}\,. \quad (4)$$

So, once the number of rivets per 8-h shift is determined for each of the three tasks, A(8) values can be estimated for each of the eight tools for each task. These estimated A(8) values can then be compared to the daily exposure action and limit values prescribed in EU Directive 2002/44/EC (2002) and repeated in Annex A of ANSI S2.70 (2006).

In this study, the ISO frequency-weighted tool handle acceleration measurements ($a_{hv(\mathrm{rms})}$) were used to estimate the maximum number of rivets an operator could drive with a particular tool in an 8-h shift at the three work tasks at Tinker AFB without exceeding the EU/ANSI DEAV of 2.5 ms^{-2} (EU Directive 2002/44/EC; ANSI S2.70-2006). This is easily accomplished by rearranging equations (3) and (4) and solving for T and the number of rivets per shift, respectively. These estimates, of course, assume that there are no additional vibration exposures during the work shift.

RESULTS

Figure 7 shows some randomly selected samples of time-history data measured at the studied work-place. Different from that reported previously (Peng, 1994; Cherng *et al.*, 2009), the vibration exposure duration for each rivet was generally >2 s in the airframe riveting process. It is also interesting to note that the impact peak generally increases with time during each riveting process, probably because the rivet becomes stiffer as it flattens. The time duration for each riveting process and the peak acceleration values of the tested rivet hammers were also substantially different from the Peng (1994) and Cherng *et al.* (2009) reports.

Figure 8 presents the average vibration spectra for each of the eight tools for the laboratory task and the three fieldwork tasks. As can be seen in the figure, the acceleration magnitude of the laboratory task was notably higher than that for the three field tasks. The spectra for the three field tasks are similar to each other.

Table 2 presents the means and standard deviations of ISO frequency-weighted acceleration ($a_{hv(\mathrm{rms})}$) for each of the eight tools as measured at the tool handle during the laboratory task and the three fieldwork tasks. Table 3 presents the results in terms of unweighted acceleration. The rankings of the tools from low to high vibration are also listed in the tables for each task. As indicated, the two Manufacturer A models and the two Manufacturer C models generally exhibited the lowest frequency-weighted and unweighted accelerations in both the laboratory and the fieldwork tasks. Tool C1 showed the lowest average frequency-weighted acceleration in all four operating situations.

Table 4 lists the rank orders of the eight tools from lowest to highest frequency-weighted and unweighted acceleration for the laboratory and for the combined field tasks. For frequency-weighted accelerations, tools C1, A1, and C2 were ranked first through third, respectively, in both the laboratory and in the actual work tasks. For unweighted vibration, tools A1, A2, C1, and C2 exhibited the lowest accelerations in the laboratory and in the field, albeit in different rank orders.

Table 5 presents the average frequency-weighted and unweighted acceleration for the laboratory task and each of the three fieldwork tasks. While the acceleration means for the three field tasks are similar to one another, the frequency-weighted acceleration measured in the laboratory was >50% higher than that measured in any of the three field tasks. For un-weighted acceleration, the laboratory average was more than double any of the fieldwork task averages.

Based on the frequency-weighted acceleration values ($a_{hv(\mathrm{rms})}$) presented in Table 2, the maximum number of rivets an operator could drive with a particular tool in an 8-h shift without exceeding the EU/ANSI DEAV of 2.5 ms^{-2} (EU Directive 2002/44/EC; ANSI S2.70-2006) were calculated for each of the three field tasks. Those calculations indicate that an operator could use any of the eight tools to drive up 3800 rivets for Field Task 1 without exceeding an A(8) value of 2.5 ms^{-2}. For Field Tasks 2 and 3, any of the tools could be used to set 4800 rivets in an 8-h shift without exceeding the EU/ANSI DEAV. Note: These estimations only consider the vibrations transmitted from the riveting hammer tool handles; additional vibration exposures during a shift could affect the daily exposure values.

DISCUSSION

The results and phenomena observed in this study provide useful information for evaluating riveting hammer vibration assessment methods. They can also be used to facilitate appropriate riveting hammer selections for the three airframes riveting tasks evaluated at Tinker AFB. The field study results can also be used in approximations of daily vibration exposures for the riveting hammer operators assigned to those tasks.

Evaluation of the laboratory-based riveting hammer test method

Tool vibration magnitudes can vary greatly in real working conditions. It is very difficult to design a standardized laboratory test method that can represent all workplace environments. Operating tools against a stable load seems to be a reasonable approach for standardizing tool evaluations for the purpose of comparing and screening tools. From this point of view, the tool loading method prescribed by ISO 8662-2 (1992b) or ISO 28927-10 (2011) seems reasonable for the following two reasons: (i) the prescribed loading device is relatively simple and can be consistently replicated according to the design required by the standard and (ii) the loading device provides a fairly stable loading condition, as reflected by the easily achieved intrasubject variation (CV < 15%).

As shown in Fig. 8, the spectra measured in the laboratory test were generally of higher magnitude than those measured at the workplace. This is partially due to differences in the work materials. This is also partially because the tool bit impacted the load throughout the entire measurement period in the laboratory tests, but during the workplace riveting process, there were intervals of no impacts during the measurement periods. In general, longer times of non-impact resulted in lower spectra magnitudes for the same number of rivet sets. Because the time required for the operator to shift from one rivet to the next depended on the specific working station, the location of the rivets on the airframe, and differences in worker riveting styles, the actual time required for completing the same number of rivets varied during the workplace evaluations. To standardize the exposure assessment and to achieve fair tool comparisons, the accelerations were averaged over periods of 30 s for every trial of the field test. As also shown in Fig. 8, the basic trends of vibration spectra as functions of frequency measured in the laboratory were similar to those measured in the field. The basic trends measured at the three workstations were also similar. These observations suggest that although the magnitude of the vibration could vary, the basic vibration characteristics of each riveting hammer remain consistent across various loading conditions; the vibration characteristics primarily depend on the functional design and mechanical properties of the hammer. Therefore, it is reasonable to use results measured under controlled conditions to compare and screen the tools according to their vibration emissions. As indicated in Table 4, the rank order of the tools identified from the laboratory test was fairly consistent with that identified from the field test, especially for the lower vibration tools. This also suggests that the laboratory test method is basically acceptable for a preliminary evaluation and selection of riveting hammers.

However, as presented in Table 5, the average frequency-weighted acceleration measured in the laboratory was >50% higher than what was measured in any of the three field tasks. For unweighted acceleration, the laboratory average was more than double any of the fieldwork task averages. These observations indicate that in general, the results of these laboratory tests should not be used for estimating workplace riveting hammer HTV exposures.

It should be noted that the ISO standardized laboratory test (ISO 8662-2, 1992b; ISO 28927-10, 2011) requires the riveting bit and anvil disc to be one entity or firmly connected. However, in the current study, the bit and anvil disc were separated. This alteration was made primarily because most of the original anvil bits for the riveting hammers were not compatible with the ISO-prescribed design of the energy absorber. The cost of specialized bits meeting the requirements of the standard would not only increase the cost of the test but would likely alter the dynamic features of the original bit. Another important factor was the fragility of the bit-anvil disc connections, especially if they are welded together. In our previous research using the ISO standardized apparatus (Dong *et al.*, 2004), we experienced repeated bit-anvil disc failures, which added substantial time and cost to the study. This minor revision to the laboratory test is similar to one of the features of the loading device proposed by the PNEUROP Tools Committee (PNEUROP, 2005). Such a change may be included in the future revisions of the standardized test.

The results of this study also confirmed that tool handle vibration can vary by operator. This may be one of the reasons that the rank ordering of the tools based on the laboratory test results was not exactly the same as that observed in the field tests. Only three tool operators are required in the ISO standardized laboratory test. However, such a small sample is unlikely to sufficiently represent the general populations of riveting hammer operators at many workplaces. This is likely one of the major reasons why the vibration magnitudes of the same tools measured in different laboratories could be significantly different. This may make it difficult to compare tool vibration emission data reported by different laboratories or tool manufacturers. On the other hand, tool tests could become too expensive and impractical if a statistically sufficient number of subjects is required in the test. A practical solution to such an issue is to include a standard reference tool in each series of tool tests and to normalize the test data with respect to that reference tool. Such a practice may not only resolve the issue of subject-induced variations but might also minimize measurement variations resulting from possible changes to the properties of the loading device. This may also be one of the improvements considered in further revisions to the standard.

Selection of riveting hammers

The frequency-weighted acceleration values measured at the workplace listed in Table 2 are generally lower than those previously reported (Burdorf and Monster, 1991; Cherng *et al.*, 2009). A similar phenomenon was also observed in their corresponding unweighted acceleration values. The lower acceleration values observed in the present study may be partially due to differences in the riveting paces employed in these studies. This may also be due in part to improvements to the new riveting hammer models evaluated in the current study as compared to the older models studied in the previous research.

Among the tools tested in the current study, Tool C1 consistently exhibited the lowest vibration emissions. Tools A1, A2, C1, and C2 generally showed lower accelerations than Tools B1, B2, D1, and D2. However, it should also be noted that tool selections should not be based entirely on tool vibration measurements. Other criteria such as productivity, tool weight, handle comfort, worker acceptance, initial cost, and maintenance costs may also be considered in the tool selection.

Vibration exposure estimates

To achieve the major goals of this study, only the vibrations on the riveting hammer handles were measured. Based on the measurements presented in Table 2, Tinker AFB sheet metal mechanics could drive at least 3,800 rivets during an 8-h shift using any of the eight tools for any of the three assessed tasks and remain below the EU Directive (EU, 2002) and ANSI S2.70 (2006) DEAV of 2.5 ms^{-2}, provided there are no additional HTV exposures during the shift. The supervisors of these work areas indicated that their riveting hammer operators would seldom drive >300–400 rivets in a shift, and they would never drive >1000 rivets in a shift. The maximum A(8) values for the tools and tasks evaluated would be 0.78 ms^{-2} and 0.90 ms^{-2} for 300 and 400 rivets, respectively. Even at 1000 rivets, the maximum estimated A(8) value would be 1.42 ms^{-2}, which is still well below the A(8) action value of 2.50 ms^{-2}. Therefore, based on the vibration emissions measured at the tool handles, none of the riveting hammer HTV exposures evaluated in this study approach the EU/ANSI action value.

However, HTV exposures in the riveting process can also include the exposure to the non-dominant hand contacting the riveting hammer housing, the riveting bit, or the airframe (Fig. 5). Also, riveting hammer operators occasionally trade places with the bucking bar operator (Fig. 6) during a shift, so those exposures would also contribute to the daily HTV exposure values. The vibrations at these locations are likely to be greater than that at the handle of the riveting hammer (Cherng *et al.*, 2009). The forces at the fingers stabilizing the front of a riveting hammer or guiding the bit are usually relatively small, and the HTV exposures in these areas are primarily localized at the fingertips. However, a bucking bar operator could apply much larger forces, and the exposure area could be more extensive. Therefore, the hands holding the bucking bar are likely to suffer more from the impact vibration exposure. This is confirmed from the fact that bucking bar operators have been reported to exhibit a much higher prevalence of vibration-induced effects than riveters who only operate riveting hammers (McKenna *et al.*, 1993). Cherng et al. (2009) reported that frequency-weighted bucking bar accelerations were at least 30% higher than corresponding values measured at the handles of the riveting hammers. Then, according to the data listed in Table 2, the weighted accelerations on the bucking bars could be greater than 2.5 ms^{-2} for some cases. On the other hand, if the bucking bar operators at Tinker AFB seldom drive >300–400 rivets in a shift, and they never drive >1000 rivets in a shift, their actual A(8) exposure levels are unlikely to exceed the DEAV. However, further study is required to confirm this hypothesis.

As mentioned in the Introduction, HTV exposures determined to be below the DEAV should not be considered to be absolutely safe, especially for high-frequency or impulsive vibration exposures. In addition to minimizing exposure times, other measures may be taken to reduce the high-frequency components of impulsive vibrations. Actions may include the use of reduced vibration riveting hammers and bucking bars. While no glove can effectively reduce low-frequency vibrations (<25 Hz), many work glove models are likely to reduce very high frequency vibrations (>1000 Hz). Hence, it is appropriate for these workers to wear gloves as long as glove use is feasible and consistent with other safety and ergonomic considerations, especially in bucking bar operations (see Fig. 6). Gloves may also help protect these workers from cuts, abrasions, and impacts while keeping the hands clean, warm, and dry. Anti-vibration (AV) gloves may provide more vibration isolation, but AV gloves may also increase grip efforts and result in early hand fatigue. AV glove use may be considered if increased grip effort and reduced finger dexterity are not concerns.

CONCLUSIONS

Although the average acceleration magnitudes of the riveting hammers evaluated in the laboratory study were considerably different from those measured in the field study, the rank orders of the tools determined in these evaluations were fairly consistent, especially for the lower vibration tools. This suggests that the standardized laboratory-based riveting hammer assessment method is acceptable for identifying tools that could be expected to exhibit lower vibrations in workplace environments. However, the large differences between the accelerations measured in the laboratory and field suggest that the standardized laboratory-based tool assessment is not suitable for estimating workplace riveting hammer HTV exposures. This study also identified tools that exhibited the lowest frequency-weighted and un-weighted accelerations in both the laboratory and the fieldwork tasks. Based on the weighted accelerations measured at the tool handles, the sheet metal mechanics assigned to the three tasks at the studied workplace are unlikely to exceed the daily vibration exposure action value (2.5 ms^{-2}) using any of the evaluated riveting hammers.

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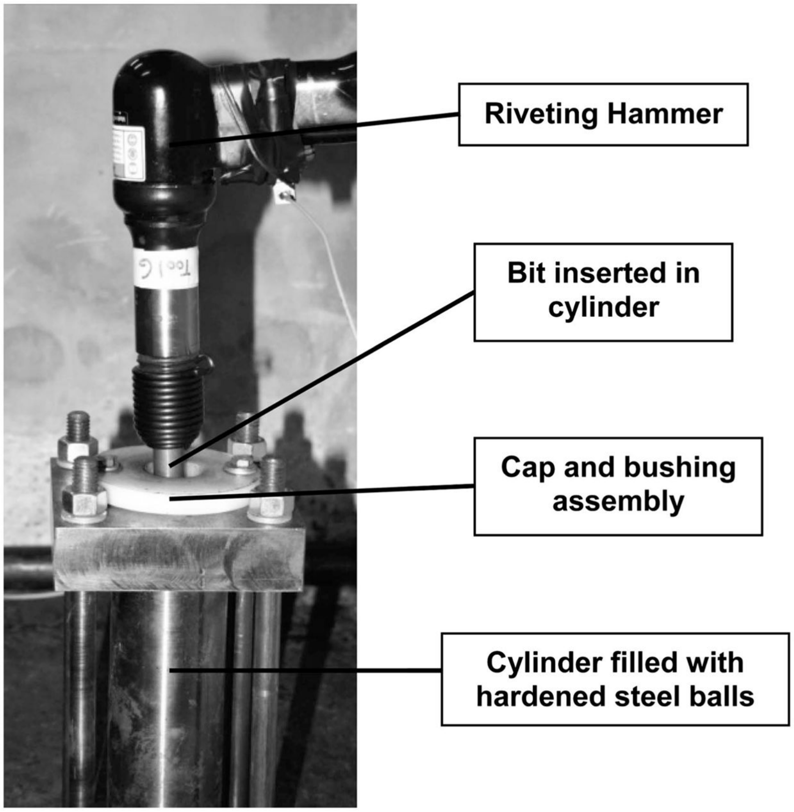

Fig. 1.

The test setup for the laboratory assessment of the riveting hammers. The riveting hammer’s bit is inserted into the energy absorber. During tool operation, the bit acts against a hardened steel disc that rests on top of the column of hardened steel balls.

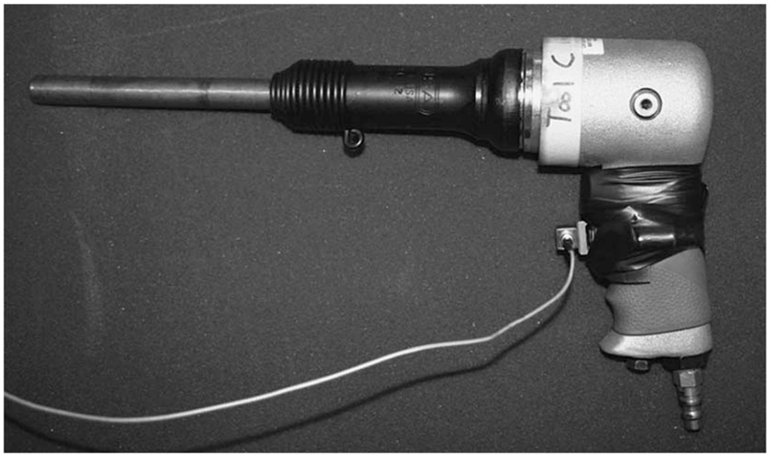

Fig. 2.

The tools were evaluated in the laboratory and field studies by measuring vibrations near the midpoint of the tool handle in the finger contact area. The triaxial accelerometers were installed on mounting blocks and secured to the tool handles with hose clamps.

Fig. 3.

Layers of synthetic rubber were used as a mechanical filter on each tool to prevent DC shifts in the acceleration measurements.

Fig. 4.

The posture used in the laboratory portion of the study. The tool operators stood on a force plate and applied a downward pushing force (feed force) on the tool handle. The tool operator maintained the specified feed force (100 ± 20 N) by monitoring the force displayed as a strip chart on a computer monitor placed directly in front of the operator.

Fig. 5.
Following the laboratory study, the eight riveting hammers were shipped to Tinker AFB for field assessment. The tools were assessed during three aircraft riveting tasks.

Fig. 6.

A bucking bar operator provides the counter force at the backside of a rivet during a trial for Field Task 1. This process was similar for the other two tasks in the field assessment.

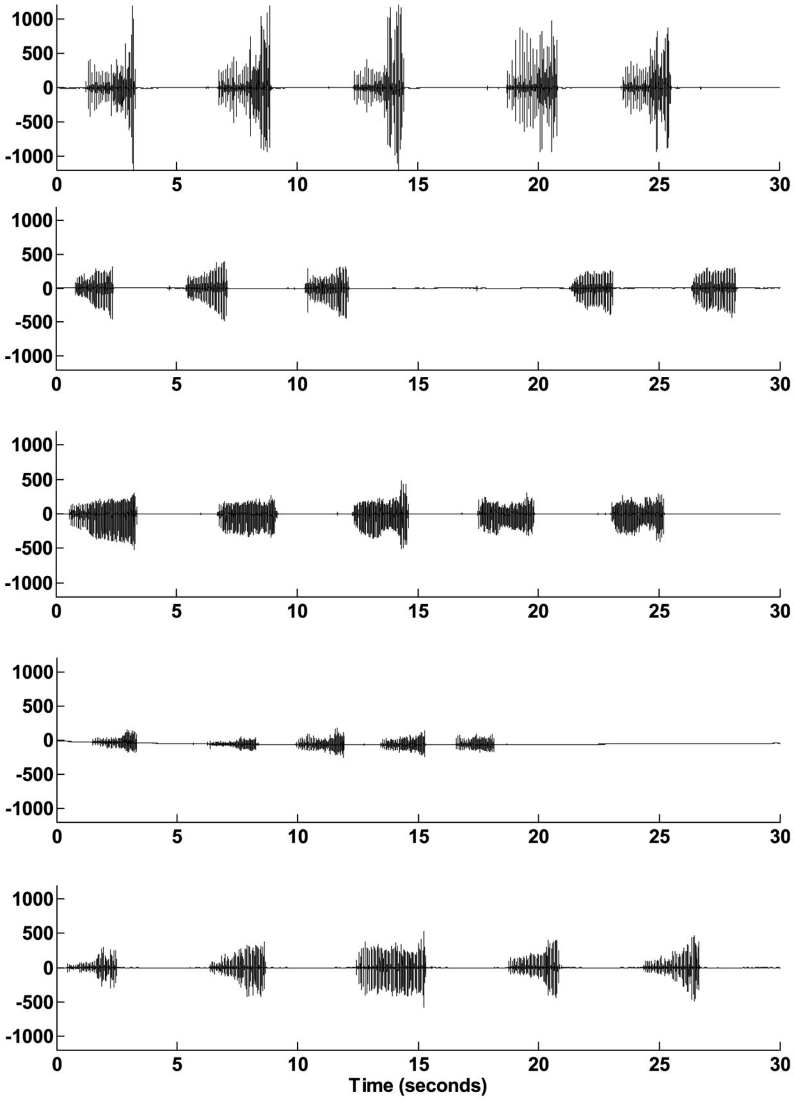

Fig. 7.

Randomly selected samples of unweighted acceleration (ms^{-2}) time-history data measured at the tool handles during 30-s trials at Tinker AFB.

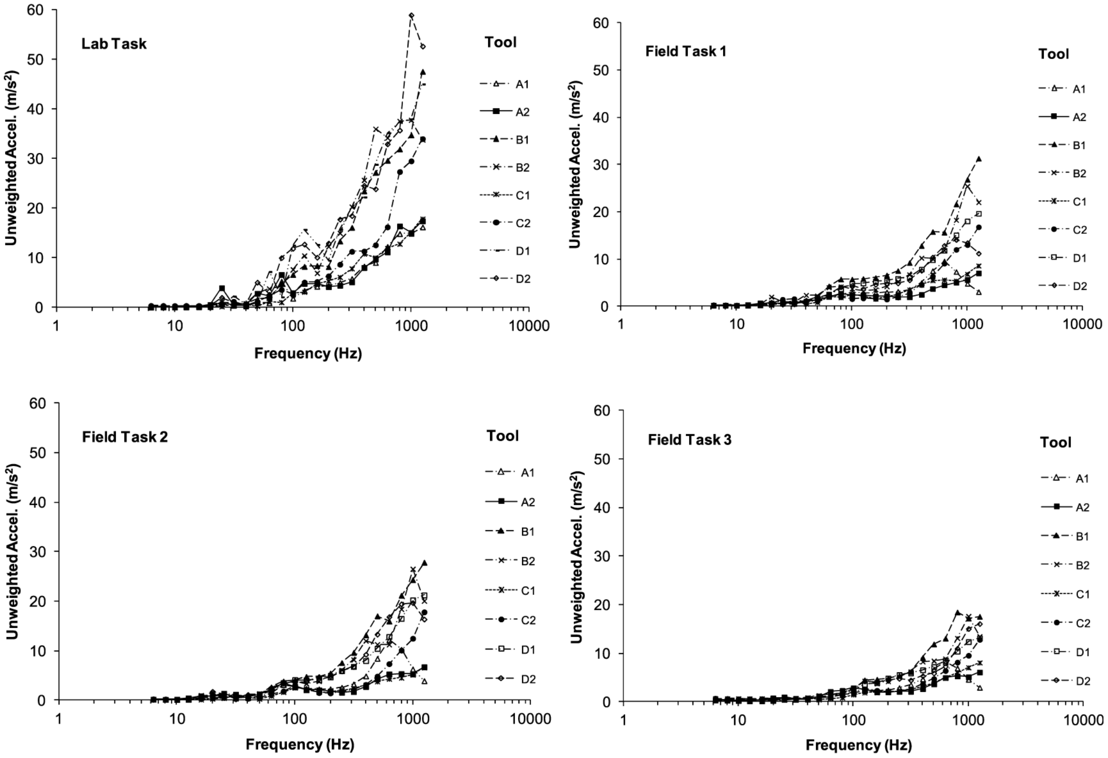

Fig. 8.

Average vibration spectra for each of the eight tools during the laboratory task and the three fieldwork tasks.

Table 1

The eight tools assessed in the study.

Manufacturer	Tool ID	Weight (kg)	Stroke (mm)
Manufacturer A	A1	1.3	102
	A2	1.4	137
Manufacturer B	B1	1.6	76
	B2	1.7	101
Manufacturer C	C1	1.3	76
	C2	1.4	101
Manufacturer D	D1	1.5	76
	D2	1.7	101

Table 2

The means and SDs of ISO frequency-weighted acceleration ($a_{hv(\mathrm{rms})}$ expressed in ms^{-2}) measured at the tool handles of the eight tools for the laboratory task and the three field tasks. The tools are also ranked from lowest to highest vibration for each task.

Tool	**Lab task**			**Field task 1**			**Field task 2**			**Field task 3**		
	$a_{hv(\mathrm{rms})}$	**SD**	**Rank**	$a_{hv(\mathrm{rms})}$	**SD**	**Rank**	$a_{hv(\mathrm{rms})}$	**SD**	**Rank**	$a_{hv(\mathrm{rms})}$	**SD**	**Rank**
C1	1.46	0.09	1	1.47	0.46	1	1.10	0.13	1	1.26	0.80	1
A1	1.84	0.12	2	1.92	0.55	3	1.68	0.27	3	1.41	0.53	2
C2	2.22	0.17	3	2.09	1.13	4	1.46	0.37	2	1.73	0.34	5
B1	3.16	0.32	4	2.79	0.28	7	2.46	0.15	8	1.85	0.35	7
A2	3.82	0.23	5	1.71	0.17	2	2.02	0.37	4	1.66	0.02	4
B2	4.54	0.35	6	3.12	1.47	8	2.29	0.44	6	2.32	1.15	8
D1	4.94	0.44	7	2.22	0.43	6	2.20	0.22	5	1.64	0.20	3
D2	5.22	0.42	8	2.10	0.11	5	2.31	0.83	7	1.77	0.54	6

Table 3

The means and standard deviations (SD) of unweighted acceleration ($a_{h(\mathrm{rms})}$ expressed in ms^{-2}) measured at the tool handles of the eight tools for the laboratory task and the three field tasks. The tools are also ranked from lowest to highest vibration for each task.

Tool	Lab task			Field task 1			Field task 2			Field task 3		
	$a_{hv(\mathrm{rms})}$	SD	Rank	$a_{hv(\mathrm{rms})}$	SD	Rank	$a_{hv(\mathrm{rms})}$	SD	Rank	$a_{hv(\mathrm{rms})}$	SD	Rank
C1	33.37	2.34	1	16.95	5.77	2	13.15	2.30	1	15.32	7.26	2
A1	35.71	2.33	2	18.57	4.32	3	21.67	5.61	3	16.22	3.97	3
C2	58.66	5.53	4	28.21	11.78	4	26.69	10.16	4	21.13	2.16	4
B1	84.72	4.45	5	56.56	3.58	8	53.14	5.01	8	38.93	5.01	8
A2	35.73	2.58	3	14.14	2.42	1	14.47	2.95	2	13.68	2.47	1
B2	97.40	4.98	7	44.84	11.46	7	45.37	12.69	7	32.09	3.76	7
D1	96.86	6.55	6	38.12	9.56	6	40.68	9.05	6	27.24	5.54	5
D2	108.04	7.37	8	32.04	1.30	5	38.31	9.00	5	28.99	2.42	6

Table 4

The rank orders of the eight tools from lowest to highest frequency-weighted and unweighted vibrations for the laboratory task and combined field tasks.

Rank	Weighted		Unweighted	
	Laboratory	**Field**	**Laboratory**	**Field**
1	C1	C1	C1	A2
2	A1	A1	A1	C1
3	C2	C2	A2	A1
4	B1	A2	C2	C2
5	A2	D1	B1	D2
6	B2	D2	D1	D1
7	D1	B1	B2	B2
8	D2	B2	D2	B1

Table 5

The average frequency-weighted ($a_{hv(\text{rms})}$) and unweighted ($a_{h(\text{rms})}$) acceleration and SD expressed in ms^{-2} for the laboratory task and each of the three fieldwork tasks.

Task	**Weighted**		**Unweighted**	
	$a_{hv(\text{rms})}$	**SD**	$a_{hv(\text{rms})}$	**SD**
Laboratory	3.40	0.27	68.81	4.51
Field 1	2.18	0.58	31.18	6.27
Field 2	1.94	0.35	31.69	7.10
Field 3	1.71	0.49	24.20	4.07