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Laboratory and Workplace Assessments of Rivet Bucking Bar Vibration Emissions

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Abstract

Sheet metal workers operating rivet bucking bars are at risk of developing hand and wrist musculoskeletal disorders associated with exposures to hand-transmitted vibrations and forceful exertions required to operate these hand tools. New bucking bar technologies have been introduced in efforts to reduce workplace vibration exposures to these workers. However, the efficacy of these new bucking bar designs has not been well documented. While there are standardized laboratory-based methodologies for assessing the vibration emissions of many types of powered hand tools, no such standard exists for rivet bucking bars. Therefore, this study included the development of a laboratory-based method for assessing bucking bar vibrations which utilizes a simulated riveting task. With this method, this study evaluated three traditional steel bucking bars, three similarly shaped tungsten alloy bars, and three bars featuring spring-dampeners. For comparison the bucking bar vibrations were also assessed during three typical riveting tasks at a large aircraft maintenance facility. The bucking bars were rank-ordered in terms of unweighted and frequency-weighted acceleration measured at the hand-tool interface. The results suggest that the developed laboratory method is a reasonable technique for ranking bucking bar vibration emissions; the lab-based riveting simulations produced similar rankings to the workplace rankings. However, the laboratory-based acceleration averages were considerably lower than the workplace measurements. These observations suggest that the laboratory test results are acceptable for comparing and screening bucking bars, but the laboratory measurements should not be directly used for assessing the risk of workplace bucking bar vibration exposures. The newer bucking bar technologies exhibited significantly reduced vibrations compared to the traditional steel bars. The results of this study, together with other information such as rivet quality, productivity, tool weight, comfort, worker acceptance, and initial cost can be used to make informed bucking bar selections.

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SUPPLEMENTARY DATA

Supplementary data can be found at http://annhyg.oxfordjournals.org/.

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Keywords

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

INTRODUCTION

Manually operated pneumatic riveting hammers used in conjunction with rivet bucking bars are widely used in the construction and maintenance of aircraft and other similar manufacturing processes. The typical aircraft riveting process involves the insertion of rivets into sheet metal comprising pre-drilled and countersunk holes. Once the rivets are in place, an operator uses an air hammer to sequentially set each rivet as it is driven against a metallic bucking bar held by a second tool operator positioned on the opposite side of the airframe. Despite new developments in robotics and other technologies, this manual riveting process remains the predominant method for fastening sheet metal to airframes (Jorgensen and Viswanathan, 2005; Cheraghi, 2008). It has been demonstrated that pneumatic riveting hammers can generate high magnitudes of impulsive vibrations (Dandanell and Engstrorn, 1986; Burdorf and Monster, 1991; McDowell *et al*., 2012). These vibrations can be effectively transmitted to the hands and fingers of the riveting hammer and bucking bar operators (Kattel and Fernandez, 1999). Such hand-transmitted vibration (HTV) has been associated with the development of hand-arm vibration syndrome (Yu *et al*., 1986; Griffin, 1990; Burdorf and Monster, 1991; McKenna *et al*., 1993). Studies have indicated that in some occupational environments, perhaps >50% of riveting tool operators could exhibit symptoms of vibration-induced white finger (a major component of hand-arm vibration syndrome) after 10 years of work (Engstrorn and Dandanell, 1986; Burdorf and Monster, 1991). It is also common to observe forceful exertions, repetitive actions, and awkward hand and finger postures during riveting operations, especially while gripping the bucking bar (Fredericks and Fernandez, 1999); these factors may account for increased incidences of carpal tunnel syndrome and other hand and wrist musculoskeletal disorders among riveters (Burdorf and Monster, 1991; NIOSH, 1997). Therefore, the control of HTV exposures to rivet workers is an important issue.

Although exposure controls may not eliminate all instances of hand-arm vibration syndrome and other disorders, it is anticipated that effective HTV exposure control strategies can help minimize harm. Therefore, many countries have adopted standards for evaluating and controlling occupational HTV exposures. Most HTV exposure standards incorporate aspects of the International Organization for Standardization (ISO) standards for measuring and assessing HTV exposures (ISO, 2001a, b). In the European Union, EU Directive 2002/44/EC on human vibration exposure requires that HTV exposure assessments be conducted in accordance with these ISO standards (EU, 2002). The EU Directive further specifies a daily exposure action value (DEAV) and a daily exposure limit value (DELV); these thresholds place upper boundaries on the daily HTV exposure values normalized to an 8-h reference period. The provisions and threshold values of the EU Directive are echoed in the US vibration HTV exposure standard (ANSI, 2006). According to the ANSI S2.70 standard, some workers exposed to HTV at levels above the DEAV will begin to exhibit symptoms associated with hand-arm vibration syndrome; for HTV exposure levels at or above the DELV, workers ‘are expected to have a high health risk’ (ANSI, 2006).

The standards mentioned above typically form the foundation for legislation or regulations that guide an employer’s HTV control program. According to the procedures, the responsibility for limiting occupational HTV exposures lies with the employer, and employers are instructed to give priority to reducing HTV at the source (EU, 2002; ANSI, 2006). In turn, employers have implemented practices for identifying and selecting tools that produce reduced vibration levels. In order to compare tool models based on their vibration emissions, the tools must be assessed while they are challenged under comparable operating conditions. Ideally, the tools should be assessed while being operated during the actual work tasks for which they are intended to be used. However, it is very difficult to standardize workplace tool assessments, as many uncontrolled factors may affect the test results.

In order to standardize such tool assessments, the ISO has developed the ISO 28927 series of laboratory-based testing standards for comparing tools according to their tool handle vibration emissions. These standards typically prescribe the postures, applied hand forces, and loading conditions under which the tools will be evaluated. For example, Part 10 of this series (ISO, 2011) pertains specifically to chipping hammers and riveting hammers. Recently, we completed a study which utilized the ISO 28927-10 standard as part of their evaluation of a number of riveting hammers (McDowell *et al*., 2012). That study found that while the ISO laboratory-based standardized method is not suitable for estimating workplace HTV exposure levels, the ISO method is acceptable for identifying riveting hammers that could be expected to exhibit lower vibrations in workplace environments.

While there is some information available regarding riveting hammer HTV exposure levels, there is very little published information pertaining to the bucking bar side of the manual riveting process. Therefore, we turned our attention to the assessment of bucking bar vibration emissions and the evaluation of new developments in bucking bar technologies. Currently, most rivet bucking bars are fabricated from ductile iron or rolled steel. While there have been a few studies on the use of denser materials such as tungsten alloys (Jorgensen and Viswanathan, 2005; Hull, 2007), there is very little information regarding workplace HTV exposures associated with bucking bar use. Although some laboratories have developed test fixtures and techniques for evaluating bucking bars (Treskog, 1994; Cherng *et al*., 2009), there is no standardized method for such evaluations.

To help establish a standardized method for evaluating and comparing rivet bucking bars, the first aim of this study was to develop a laboratory-based methodology for assessing bucking bar vibration emissions. Another objective of this study was to characterize and rank-order the vibration emissions of selected models of traditional and innovative rivet bucking bars during their use in actual workplace riveting tasks. The laboratory and workplace results and tool rankings were also compared to evaluate the newly developed laboratory test method.

METHODS

Proposed lab-based test apparatus for assessing bucking bar HTV emissions

The first major component of this study was the development of a laboratory-based apparatus and methodology for simulating a riveting task and evaluating rivet bucking bar vibrations. The proposed approach is similar to the lab evaluations presented in the ISO 28927 series for hand-held non-electric tools where sample tools within a tool group (e.g. pneumatic chipping hammers, impact wrenches, etc.) are operated by human test subjects against a specified, consistent load while the vibration emissions are measured near where the vibration enters the tool operator's hand (usually the tool handle). While there is a standardized laboratory-based method for assessing HTV emissions of riveting hammers within the ISO 28927 series (ISO, 2011), there is no such standard for evaluating rivet bucking bars. However, the laboratory-based bucking bar HTV assessment method employs several features and techniques presented in the existing ISO standardized methodologies. Similar to the ISO standards, the proposed apparatus and procedure are designed to deliver consistent forces and excitation to selected bucking bars while the vibration transmitted to the hand-tool interface is measured. The proposed test method was also designed to provide reasonable representations of the postures, applied forces, and vibration excitations observed in actual riveting tasks like those evaluated during the earlier riveting hammer study (McDowell *et al*., 2012). (For a more detailed discussion about the development of the NIOSH bucking bar test apparatus, see the Supplementary data available at *Annals of Occupational Hygiene* online.)

The proposed laboratory-based bucking bar test apparatus is depicted in Fig. 1. One of the key features of the test apparatus is its energy absorber. This energy absorber was developed by engineers at Atlas Copco Tools AB for their bucking bar test stand and procedure (Treskog, 1994). The energy absorber comprises a steel cylinder filled with hardened steel balls and is very similar to that described in the standardized method for evaluating riveting hammers and related percussive tools (ISO, 2011). In the ISO 28927-10 standard; the energy absorber is mounted vertically on a large, unmovable reinforced-concrete base, and the working end of the bit is inserted into the top of the cylinder. For the proposed bucking bar test method, the energy absorber assembly is mounted horizontally on a rigid, heavy steel base that is bolted on top of the concrete base (Fig. 1A). A remote-controlled pneumatic riveting hammer is also securely fastened to the base and functions as the source of vibration (Fig. 1B). An anvil-shaped riveting bit is inserted into the riveting hammer, and the anvil-shaped working end is, in turn, positioned inside the energy absorber. The anvil bit rests against the column of hardened steel balls inside the cylinder. At the opposite end of the energy absorber, a second steel rod with an anvil-shaped end is inserted into the cylinder to mirror the anvil riveting bit. This second rod serves as the simulated rivet. Cap and bushing assemblies are affixed to each end of the cylinder to guide the steel rods, to prevent the escape of any of the steel balls, and to trap any fragments in the unlikely event of riveting bit/simulated rivet failure. As the riveting hammer operates, energy is transferred from the riveting bit to the column of steel balls, and then to the simulated rivet. During this process, the energy absorber dissipates some of the energy which enables stable and reproducible inputs to the simulated rivet.

During the laboratory bucking bar assessments, a tool operator grasps a bucking bar with his/her dominant hand while using the non-dominant hand for additional support and control. Typical hand posture of an operator grasping an instrumented bucking bar is shown in Fig. 2. The operator presses the flat surface of the bucking bar against the vibrating simulated rivet while tri-axial acceleration at the hand-tool interface is measured. To measure the applied push force, the operator stands on a force plate (Fig. 1E) mounted on a wooden platform; the platform height is adjusted as necessary so that the operator can comfortably perform the simulated riveting task. The applied push force is displayed as a strip chart on a computer monitor placed in front of the operator (Fig. 1F).

Riveting tools

Nine brand-new rivet bucking bars were evaluated in this study. The bucking bars were selected to be compatible with the designated riveting tasks to be evaluated at a large aircraft maintenance facility during this study’s workplace evaluations. Three types of rivet bucking bars were assessed: (i) three traditional bars (Bars A, B, and C) made from cold rolled steel; (ii) three bars with the same shapes and dimensions as the traditional bars but made from a tungsten alloy (Bars D, E, and F), and (iii) three bars incorporating spring-dampeners (Bars G, H, and I). The nine bucking bars are shown in Fig. 3. Table 1 provides each bucking bar s identifier, manufacturer, model number, and type.

A brand-new Ingersoll-Rand Model AVC 13 size 4X riveting hammer was used to provide the vibration stimulus throughout the laboratory and workplace phases of the study (Fig. 4). This tool model was selected by the workplace staff because it is regularly used to perform the three workplace riveting tasks evaluated in this study.

Accelerometers and vibration data collection system

In both the lab and the field, the bucking bars were evaluated by measuring the vibration at the surface of the bucking bar in close proximity to where the vibration enters the operator’s hand. All bucking bar vibration measurements were collected via PCB Model 356B11 piezoelectric tri-axial accelerometers. The accelerometers were installed on mounting blocks and secured to the bucking bar with hose clamps (Fig. 4). Once each accelerometer installation was evaluated and the proper operation was verified, the accelerometers and mounting assemblies were wrapped with electrical tape to prevent hand contact with any sharp edges. All the bars with their mechanical filters and accelerometers installed are shown in Fig. 3.

The acceleration on the riveting hammer was also monitored and recorded during the lab and workplace studies. During the workplace evaluations, the vibrations were measured at the tool handle. In the laboratory evaluations using the NIOSH bucking bar test apparatus, the accelerometer was clamped to the body of the riveting hammer near the bit chuck. As was done with the bucking bars, a synthetic rubber mechanical filter was installed on the riveting hammer to mitigate DC shifts (Fig. 4). (Additional details about the protection against DC shifts can be found in the Supplementary data available at *Annals of Occupational Hygiene* online.)

Tri-axial vibration data were collected simultaneously from the riveting hammer and bucking bar via a portable six-channel B&K PULSE system (Brüel & Kjær, Input/Output Module Type 3032A). The vibration data collected from this system were expressed as the root mean square (RMS) values of the accelerations in the one-third octave frequency bands, with center frequencies from 6.3 to 1250 Hz. Both time-history data and frequency spectrum were recorded. To examine how the frequency weighting affects the results as is recommended in NIOSH Publication #89–106 (NIOSH, 1989), the bucking bars were rank-ordered by band-limited unweighted tool handle acceleration as well as by frequency-weighted acceleration. The vector sum, or 'total' values of the unweighted RMS accelerations were computed using the following formula:

$$a_h = \sqrt{a_{hx}^2 + a_{hy}^2 + a_{hz}^2} \quad (1)$$

where a_h is the unweighted root-sum-of-squares total value, and a_{hx}, a_h, and a_{fe}, are the unweighted RMS acceleration 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 (ISO, 2001a):

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

where a_{hw} is the single-axis 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-weigh ted values are computed using

$$a_{hv} = \sqrt{a_{hwx}^2 + a_{hwy}^2 + a_{hwz}^2} \quad (3)$$

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

Trial runs

In accordance with the manufacturer's recommendations, the riveting hammer was lubricated and broken in prior to the study through a series of trial runs at the NIOSH laboratory. The trial runs were also used to verify proper installations of all accelerometers and their mechanical filters, to calibrate all accelerometers, and to test the operation of the vibration data collection system. The trial runs were divided between the NIOSH bucking bar test apparatus described above and a second station where two tool operators, one riveter and one bucker, fastened sheet metal to a steel frame mounted on a concrete base. This second station was designed to closely mimic the workplace tasks; the specifications for the rivets, sheet metal, and frame were based on those components commonly used for the three designated workplace tasks. These trial runs were also used to determine the proper target push force to be used in the laboratory tests. Following the trial runs and calibration trials, the nine rivet bucking bars along with the riveting hammer were shipped to the aircraft maintenance facility with their accelerometers installed.

Workplace data collection

Three riveting tasks at the aircraft maintenance facility were identified by the workshop staff for the workplace HTV evaluations. These were the same three riveting tasks assessed in the earlier riveting hammer study (McDowell *et al*., 2012). All three tasks involved riveting the sheet metal ‘skins’ to the ‘ribs’ of the airframes. The first task consisted of attaching sheet metal to the side cowls of a large military aircraft. The second and third tasks involved the attachment of sheet metal to the spoilers and elevators of another type of military aircraft, respectively. The workstations for the three tasks are shown in Fig. 5.

The riveting hammer and bucking bars were operated by expert sheet metal mechanics regularly assigned to these specific work tasks at the maintenance facility. Three bucking bar operators for each of these tasks (a total of nine bucking bar operators) were selected by the workshop staff to operate the nine bars. Over the course of the evaluation, each operator completed three trials with each bucking bar. The bucking bar order was randomized for each operator. Because the riveting processes for these selected work tasks require two workers, additional sheet metal mechanics were needed to operate the riveting hammer. One riveting hammer operator worked with all three bucking bar operators on a specific task.

Prior to testing, the three bucking bar operators and the riveting hammer operator were briefed on the testing procedure. Before a set of trials began, a NIOSH engineer prepared the designated bucking bar for operation and data collection. The engineer handed the prepared bucking bar to the bucking bar operator who, along with the riveting hammer operator, positioned themselves to complete the first trial. A trial consisted of the complete setting of exactly five rivets within a 30-s span. At the ‘START’ command given by the NIOSH investigator, the bucking bar and riveting hammer operators set five individual rivets in 30 s or less. Data collection commenced at the ‘START’ command and lasted exactly 30 s. The bucking bar operators used the same riveting techniques (posture, forces, etc.) that are normally employed to complete the sheet metal attachment task. Once the fifth rivet in the trial was set, the bucking bar operator rested for a few seconds while the data file was saved. Once the file was saved, the tool operators were prompted to get ready for the next trial. This process was repeated until the tool operators completed three consecutive five-rivet trials with the designated bucking bar. At the end of the third trial, the data were checked for obvious errors. If timing or other errors were detected, trials were repeated until a full three-trial dataset was collected for that bucking bar/operator combination. Once a three-trial set was complete, the bucking bar operator handed the bucking bar back to the engineer who then prepared the next bucking bar in the sequence for use by the second bucking bar operator. The process was then repeated. This progression continued until all three bucking bar operators completed three-trial datasets for each of the nine bucking bars.

On the following day, the riveting tools and vibration data collection system were relocated to the Task 2 work area for the second day of data collection. The above-described procedure was repeated in full with a different set of bucking bar operators and a different riveting hammer operator. Likewise, once Task 2 data collection was complete, the data collection system and tools were moved to the Task 3 work area on the third day of data collection, and the tool operation and data collection procedures were repeated with the third set of riveting tool operators.

Laboratory data collection

Following the workplace data collection sessions, the riveting hammer and the nine bucking bars were shipped back to NIOSH and further evaluated at the NIOSH hand-arm vibration laboratory. Identical test matrix and data collection schemes were employed in the lab and in the field. In the laboratory phase, the locally recruited test subjects were experienced tool operators, but they were novice riveters. With informed consent, the recruited tool operators followed a protocol designed to mimic the vibration exposure sequence experienced by the workers at the aircraft maintenance facility. The laboratory study protocol was reviewed and approved by the NIOSH Human Subjects Review Board.

Each bucking bar operator underwent a familiarization period with the bucking bar operation, the simulated riveting cycles/vibration generated by the test apparatus, and with the push force monitoring system. If necessary, the platform height was adjusted to ensure comfort and proper work posture. The operator performed a number of practice trials. Once comfortable with the procedure, the operator began the series of data collection trials.

During the test, the on/off operation of the riveting hammer mounted on the test apparatus was controlled remotely via a control station manned by the NIOSH investigator. The control station comprised a repeat-cycle timer that was programmed to automatically cycle power to the tool supply air solenoid valve which cycled the riveting hammer on and off in order to simulate the typical pace of the workplace airframes riveting tasks. (The Supplementary data available at *Annals of Occupational Hygiene* online shows a schematic diagram of the control circuit.) The simulated riveting cycle consisted of 2 s on time and 3 s off time per rivet. To mimic the workplace evaluations, a trial in the NIOSH lab test simulated the setting of 5 rivets in 30 s.

Like the workplace evaluations, the bucking bars were presented to the operators in a pre-determined random order. To begin a trial, the operator was instructed to press the flat surface of the bucking bar against the simulated rivet with the specified push force (80 ± 10 N). Once the push force was observed to be stable, the NIOSH investigator initiated a 30-s vibration exposure/data collection trial by pressing the start button on the remote-control station. The bucking bar operator was instructed to try to maintain a steady push force while the simulated rivet cycled through the 5-rivet sequence. At the end of the 30-s trial, the operator rested for at least 1 min. The bucking bar operator completed three consecutive trials with each bucking bar. At the completion of three trials, the coefficient of variation

(C_v) of the ISO frequency-weighted total value (a_{hv}) was immediately calculated for those trials. As is specified in the ISO 28927 series of standards, trials were repeated if the C_v was found to be 0.15 or greater. Vibration measurements proved to be fairly consistent as less than 10% of all trials required replication.

Data analysis

Bucking bar comparisons made in this study were primarily based on the ISO frequency-weighted bucking bar vibration measurements (a_{hv}) recorded and analyzed in accordance with ISO 5349-2, 2001 (ISO, 2001b) and ANSI S2.70–2006 (ANSI, 2006). The bucking bars were also rank-ordered by unweighted, band-limited (6.3–1250 Hz) bucking bar acceleration (a_h). Rank orders were determined for each of the three workplace riveting tasks, the three-task workplace average, and for the laboratory vibration values.

General linear models of analysis of variance (ANOVA) for acceleration were conducted to evaluate the influence of bucking bar type (three levels: cold rolled steel, tungsten alloy, and dampened) and task (three workplace tasks and one lab task) on the bucking bar HTV emissions. Separate analyses were completed for the laboratory, workplace, and combined results. Tukey honestly significant difference (HSD) post hoc pairwise comparisons were also performed. Pearson correlation analyses were conducted to examine the relationship between riveting hammer and bucking bar accelerations. All statistical analyses were performed using SPSS statistical software (IBM SPSS Statistics, version 19.0). Analysis results were considered significant at the $P < 0.05$ level.

RESULTS

Bucking bar acceleration

Table 2 contains the frequency-weighted and unweighted acceleration averages for each bucking bar for each of the three workplace tasks as well as for the laboratory task. The bucking bars are ranked from 1 (lowest) to 9 (highest) according to the average frequency-weighted acceleration for each task.

The ANOVA for frequency-weighted bucking bar acceleration for the workplace assessments revealed that bucking bar type ($F_{2,234} = 72.5$; $P < 0.001$), task ($F_{2,234} = 17.3$; $P < 0.001$), and the task by bar type interaction ($F_{4,234} = 6.4$; $P < 0.001$) were all significant factors. For unweighted bucking bar acceleration, bucking bar type ($F_{2,234} = 35.1$; $P < 0.001$) and task ($F_{2,234} = 8.2$; $P < 0.001$) were both significant, but the task by bar type interaction was not significant ($F_{4,234} = 1.4$; $P > 0.221$). Post hoc Tukey tests showed that the tungsten bucking bars had significantly lower weighted and unweighted acceleration than both the cold rolled steel and dampened bars ($P < 0.001$). The steel bars exhibited significantly higher weighted acceleration than the tungsten and dampened bars ($P < 0.001$), but the steel bars were not significantly different than the dampened bars in terms of unweighted acceleration ($P > 0.997$). Task 3 had a significantly higher unweighted acceleration mean than the other two workplace tasks ($P < 0.005$), while there was no significant difference between Tasks 1 and 2 ($P > 0.821$). For weighted acceleration, all workplace tasks were significantly different from each other ($P < 0.001$) with Task 1 having the highest mean and Task 2 having the lowest.

The analyses for the laboratory assessments showed that each of the three bucking bar types was significantly different from the other two types in terms of both weighted and unweighted bucking bar acceleration ($P < 0.001$). The steel bar vibration mean was significantly higher than the other two bar types in regards to both weighted and unweighted acceleration. However, the tungsten bars exhibited significantly lower unweighted acceleration than the dampened bars while the opposite was true for weighted acceleration.

The ANOVA for weighted bucking bar acceleration for the combined lab and workplace assessments revealed that task ($F_{3,474} = 186.7$; $P < 0.001$), bucking bar type ($F_{3,474} = 139.4$; $P < 0.001$), and the task by bar type interaction ($F_{6,474} = 19.3$; $P < 0.001$) were all significant factors. The ANOVA results for unweighted bucking bar acceleration were similar as task ($P_{3,474} = 39.9$; $P < 0.001$), bucking bar type ($F_{3,474} = 66.8$; $P < 0.001$), and the task by bar type interaction ($F_{6,474} = 5.9$; $P < 0.001$) were all significant. The workplace tasks produced significantly higher weighted and unweighted accelerations than the laboratory task ($P < 0.001$). The Tukey tests showed that the tungsten bucking bars had significantly lower weighted and unweighted acceleration than both the cold rolled steel and dampened bars ($P < 0.018$). The steel bars exhibited significantly higher weighted acceleration than the tungsten and dampened bars ($P < 0.001$), but the steel bars were not significantly different than the dampened bars in terms of unweighted acceleration ($P > 0.183$).

Laboratory and workplace bucking bars rank orders

The average one-third octave band frequency spectra for each bucking bar for the laboratory and workplace assessments are pictured in Fig. 6. As can be seen in the figure, the bucking bars tended to exhibit larger high-frequency spectrum components in the workplace tasks as compared to the laboratory task.

The rank orders of the nine bars in terms of unweighted and weighted acceleration for the lab and workplace are depicted in Fig. 7. In terms of unweighted acceleration, the laboratory ranking for every bar was within two places of its corresponding workplace ranking. For weighted acceleration, the rankings for four of the nine bars were identical in the lab and workplace. The rankings for three other bars were within one place of one another. However, the lab and workplace rankings for two of the bars (D and I) were considerably different. Table 3 presents the average rankings of the bucking bars by group. For unweighted acceleration, the laboratory group rankings were very similar to the workplace group rankings. For weighted acceleration, the steel bars were ranked as the group with the highest acceleration in both the lab and the workplace, but the rankings for the tungsten and dampened bars were more inconsistent. As indicated in Tables 2 and 3 and Fig. 7, in terms of both frequency-weighted and unweighted acceleration, the steel bucking bars were generally among the bars exhibiting the highest vibrations in both the workplace and the lab. The rankings for the tungsten and dampened bars were more mixed depending on the study site and the application of frequency weighting.

Comparing riveting hammer with bucking bar acceleration

Table 4 presents the frequency-weighted and unweighted acceleration averages for the three types of bucking bars and for the riveting hammer for the lab and the workplace evaluations. As expected, the riveting hammer vibration measurements were much more consistent across bar types in the laboratory as compared to the workplace. Interestingly, the riveting hammer exhibited lower unweighted acceleration in the workplace but slightly higher weighted acceleration. In the lab, each type of bucking bar exhibited lower weighted acceleration than the riveting hammer. In the workplace, the steel bucking bar weighted acceleration average was significantly higher than that for the riveting hammer while the riveting hammer displayed higher weighted accelerations than the tungsten bars and the dampened bars. Pearson correlation analyses did not reveal any significant relationships between the riveting hammer accelerations and bucking bar accelerations ($P \geq 0.14$).

DISCUSSION

Laboratory vibration exposures versus workplace exposures

As shown in Fig. 6, the spectra measured in the workplace evaluations were generally of higher magnitude than those measured in the laboratory, especially at the higher frequencies. The greater flexibility of the workplace structure as compared to the laboratory apparatus likely contributed to the increased high-frequency content of the workplace acceleration spectra. As presented in Table 4, the average frequency-weighted acceleration measured in the workplace for the steel and dampened bucking bars was about twice what was measured in the laboratory for the same bars. Similarly, the frequency-weighted acceleration for the tungsten bars was about 50% higher in the workplace as compared to the lab. For unweighted acceleration, the workplace bucking bar averages ranged from 1.2 to 1.9 times the laboratory averages. For the riveting hammer, the workplace weighted acceleration averages were about 20% higher than the laboratory averages while the laboratory unweighted riveting hammer acceleration averages were about 25% higher than the workplace averages. These observations indicate that in its present configuration, the NIOSH laboratory-based bucking bar vibration assessment method is not suitable for estimating workplace bucking bar HTV exposures.

However, as noted in Laboratory and Workplace Bucking Bars Rank Orders section above, the laboratory-based method did a reasonable job of ranking the bars in terms of vibration magnitude. Bucking bar and riveting hammer vibration varied by task and by operator. Some of this variation can be explained by the fact that the bucking bar operators in the workplace trials self-selected the rivets to be set based on which bucking bar they were presented. It was observed that for the bulkier bucking bars, some of the operators generally chose rivets in open areas of the airframe and saved rivets near the corners and edges for the smaller bucking bars. Thus, some of the bucking bars might have been systematically subjected to higher or lower vibration stimuli depending on the relative rigidity of the rivet location. The effect of relative rivet location on the measured acceleration is unknown, but this uncontrolled variable might have introduced some bias into the workplace bucking bar rankings. Randomizing or balancing rivet location might have improved the correspondence between the laboratory and workplace rankings.

During preliminary laboratory evaluations, it was observed that if the operator applied too much feed force, the spring of a dampened bucking bar could bottom-out, and thus the dampening mechanism was defeated. The amount of force required to bottom-out the dampeners varied by bar model, but ranged from around 90 N up to about 120 N. While this was not a problem in the laboratory trials where the target feed force was 80 N, it is very possible that that there were instances when the operators in the workplace applied enough force to overcome the dampeners. This may explain the discrepancies between the workplace and laboratory rankings for the dampened bars, especially bucking bar I.

Bucking bar vibration versus riveting hammer vibration

In the workplace evaluations, the averages for frequency-weighted and unweighted acceleration for the traditional steel bucking bars were substantially higher than those for the riveting hammer. This is consistent with earlier studies which compared the vibration exposures for riveting hammers and conventional bucking bars (Engstrom and Dandanell, 1986; Cherng *et al*., 2009). On the other hand, the tungsten and dampened bucking bars exhibited lower weighted accelerations than the riveting hammers in the workplace trials, while all bars showed greater unweighted acceleration averages than the riveting hammer. While the newer technologies (tungsten and dampeners) significantly reduced the weighted HTV exposures for the bucking bar operators, the exposures to the riveting hammer operators increased. This apparent trade-off may need further examination and should be considered when contemplating bucking bar selections.

The workplace riveting hammer acceleration averages were considerably higher in the present study than those observed in our earlier riveting hammer study at the aircraft maintenance facility (McDowell *et al*.,2012). While the same riveting tasks were evaluated in both studies, the riveting hammer vibration measurements are not directly comparable because the studies employed different riveting tools and different operators. More importantly, as mentioned before, the time that the riveting hammer was operating during a measurement trial in the workplace evaluations was neither measured nor controlled; the observed riveting hammer acceleration differences were likely due in part to variations in the amount of ‘on’ time during the workplace riveting trials.

New bucking bar technologies versus traditional designs

While the newer bucking bar technologies performed favourably compared with the traditional steel bucking bars, there are some trade-offs that should be considered. Overall, the tungsten bucking bars exhibited significantly lower accelerations than their similarly-shaped steel bars in terms of both weighted and unweighted acceleration. This was true in both the laboratory and workplace evaluations. This observation is consistent with earlier studies that also compared the heavier tungsten alloys with traditional steel bars (Jorgensen and Viswanathan, 2005; Hull, 2007). However, as noted in Table 1, the tungsten-based bars are twice as heavy as their steel counterparts. This increased mass is effective for attenuating vibration, but the added tool weight could result in other ergonomic issues. Furthermore, the harder tungsten alloys are more brittle and difficult to machine than the traditional steel bars; this may limit the shapes and sizes of bars available in tungsten. Also, the tungsten bars are much more expensive than traditional steel bars.

The bucking bars featuring spring-dampeners also exhibited significantly lower frequency-weighted accelerations than the steel bars in both the laboratory and in the workplace. While these bars are similar in weight to the traditional steel bars evaluated in this study, the somewhat bulky vibration dampeners might limit their applications near frame edges or other tight spots. Like the tungsten bars, the dampened bucking bars cost considerably more than traditional steel designs.

CONCLUSIONS

The results of this study suggest that the laboratory-based NIOSH method shows promise as a technique for identifying rivet bucking bar designs that may reduce workplace HTV exposures to sheet metal workers. However, there were considerable differences among the laboratory and workplace acceleration measurements. The results of the laboratory tests should not be used as a substitute for risk assessments of workplace bucking bar vibration exposures.

This study found that as a group, the traditional cold-rolled steel rivet bucking bars exhibited significantly higher frequency-weighted accelerations in both the laboratory and the workplace tasks than comparably shaped tungsten bars and similarly sized bucking bars incorporating spring-dampeners. The results of this study, together with other information such as, rivet quality, productivity, tool weight, comfort, worker acceptance, and initial cost, can be used to help appropriately select rivet bucking bars.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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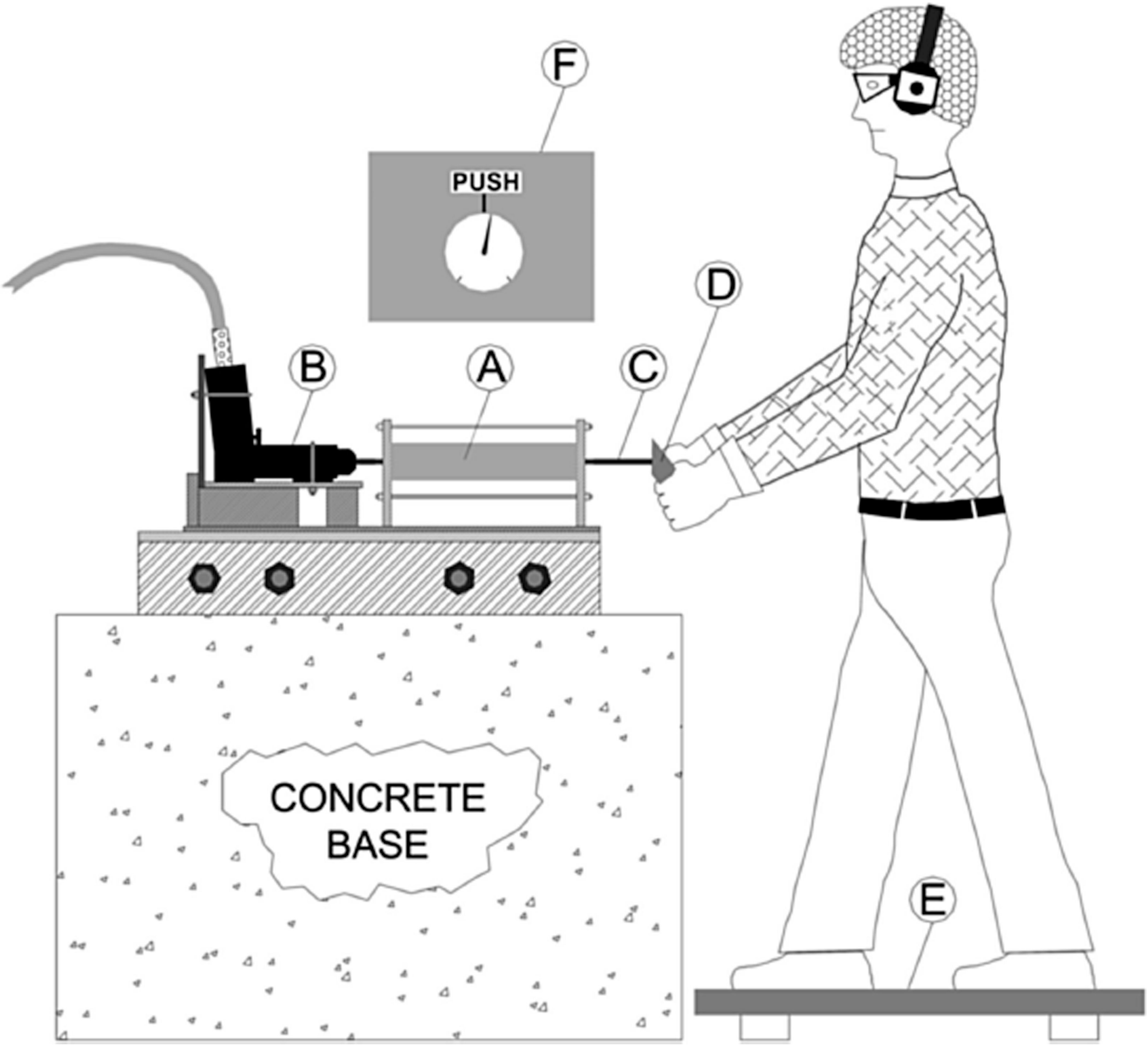

Figure 1.

Experimental setup and typical posture of the bucking bar operator pressing the bar against the simulated rivet. (A) Energy absorber dampens the vibration input to the simulated rivet; (B) Remote-controlled pneumatic riveting hammer programmed to deliver consistent vibration stimuli; (C) Simulated rivet; (D) Bucking bar is pressed against the simulated rivet; (E) Force plate measures the ground reaction force (push force); (F) Computer monitor displays the applied push force allowing the bucking bar operator to maintain the force within the specified range.

Figure 2.

The bucking bar operator grasped the bar with the dominant hand and used the other hand to help support and control the tool. The operator pressed the bucking bar against the simulated rivet with a push force of 80 ± 10 N.

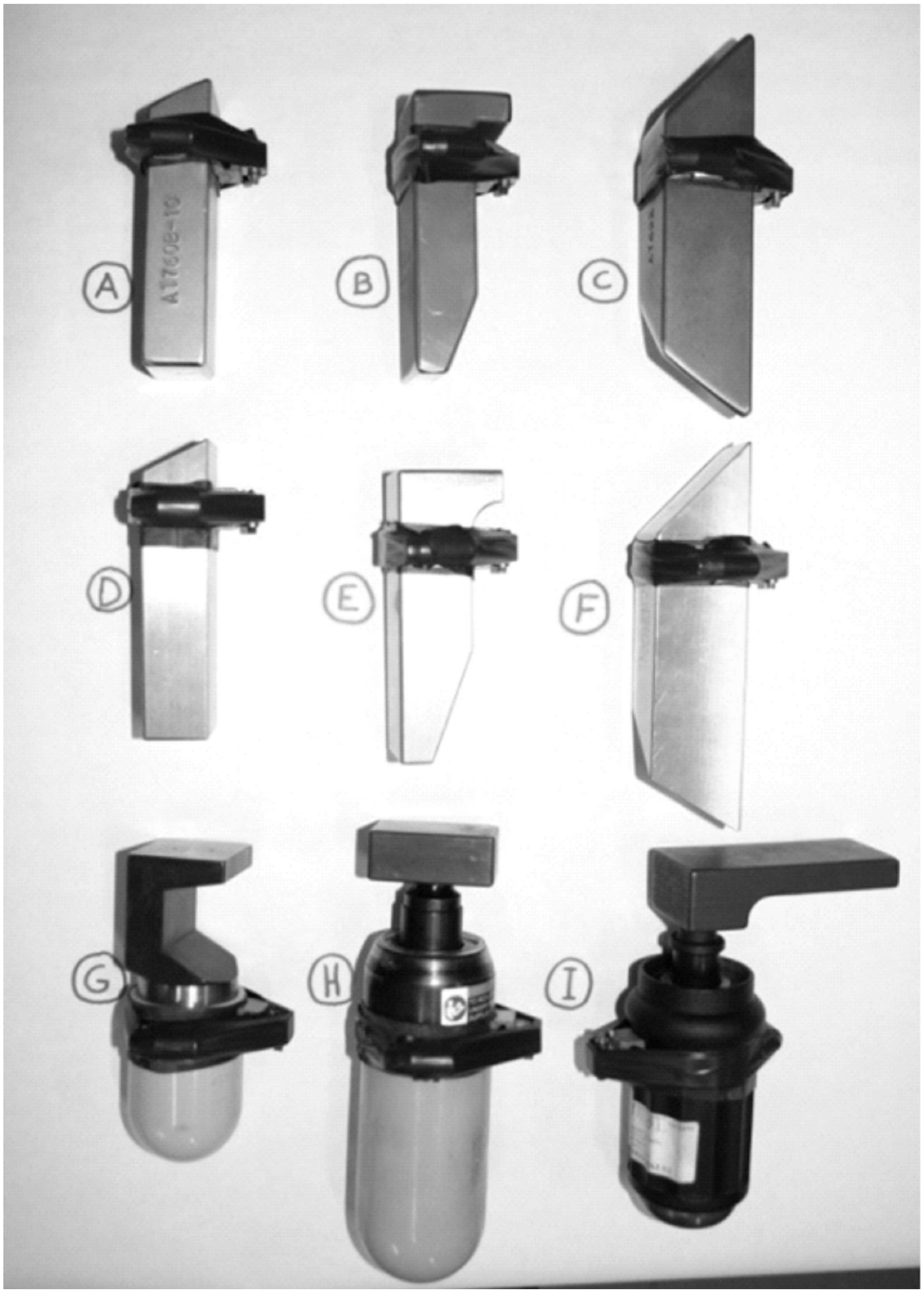

Figure 3.
The nine bucking bars shown with tri-axial accelerometers mounted.

Figure 4.

The accelerometer mounting technique. Synthetic rubber was used as a mechanical filter on each bucking bar to prevent DC shifts in the acceleration measurements. As can be seen in Fig. 3, electrical tape was wrapped around the accelerometer and clamp to prevent hand contact with sharp edges. This same technique was used to mount the accelerometer on the handle of the riveting hammer.

Figure 5.

The three workplace tasks evaluated at a large aircraft maintenance facility. Task 1: riveting skins and ribs for the side cowls of a large military airplane; Task 2: riveting skins and ribs for the spoilers of a large refueling airplane; Task 3: riveting skins and ribs for the refueling airplane elevators.

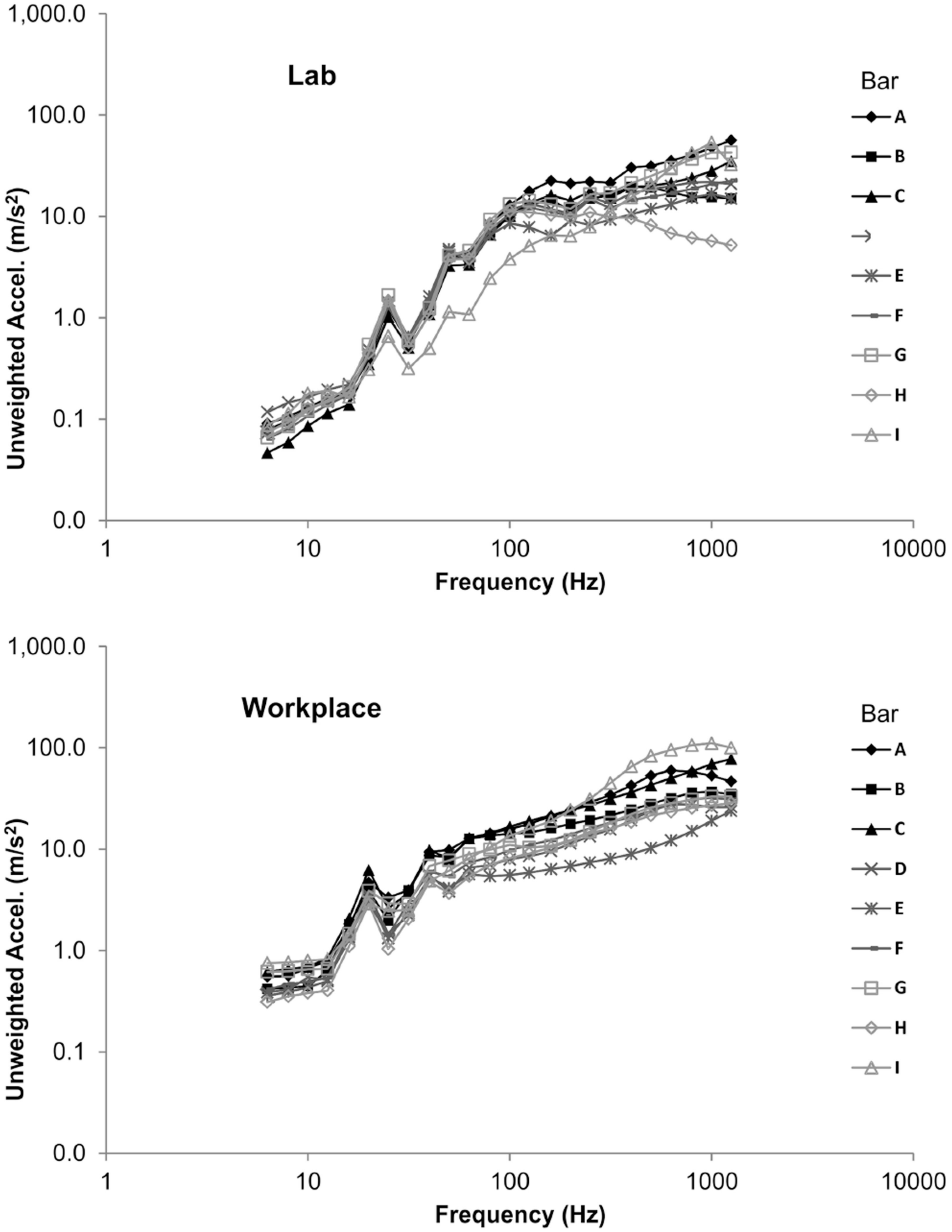

Figure 6.

The average one-third octave band frequency spectra for the nine bucking bars in the lab and in the workplace.

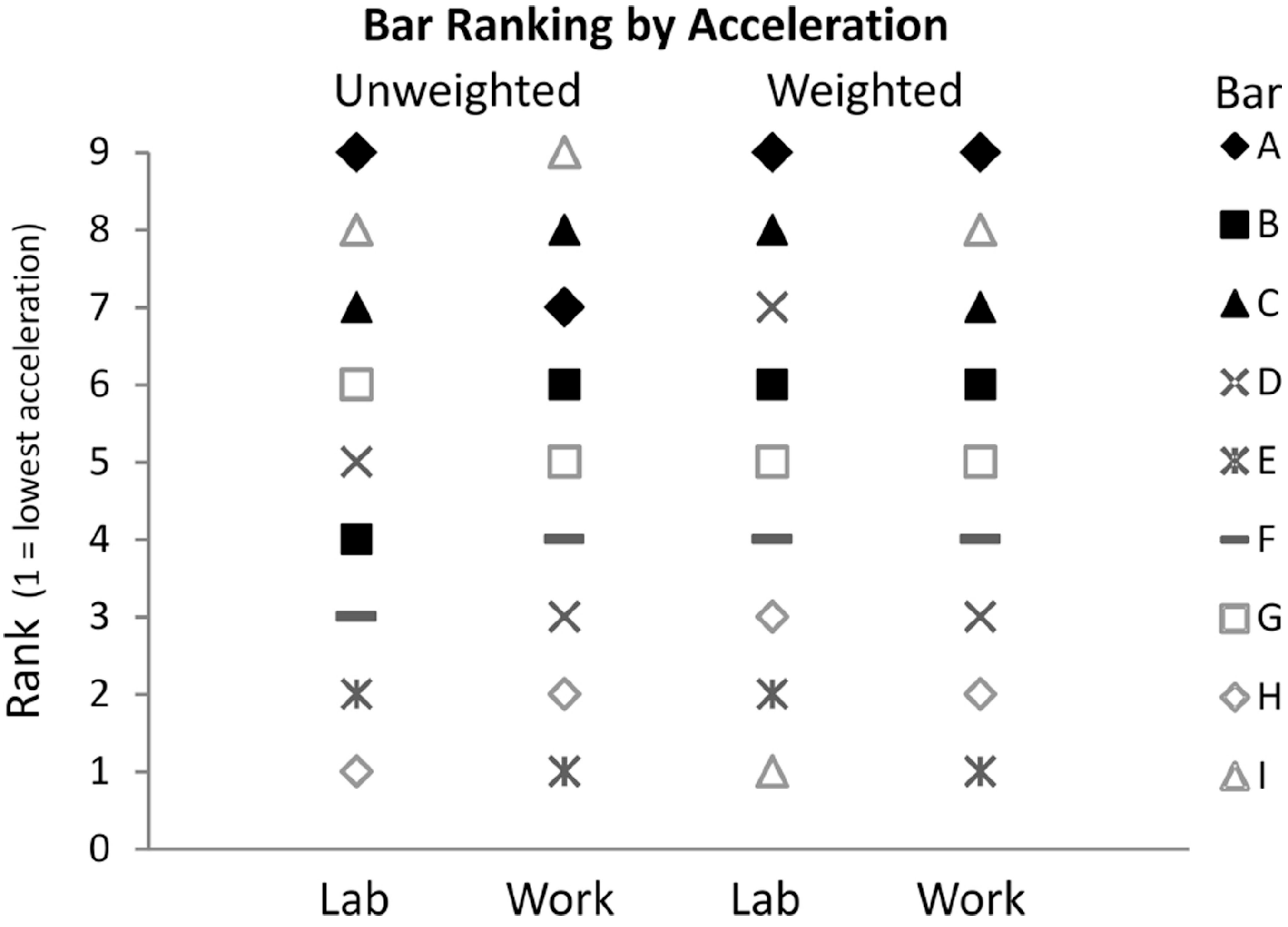

Figure 7.

The nine bucking bars ranked by unweighted and weighted acceleration for the lab and workplace evaluations.

Table 1

The nine bucking bars assessed in the study

Bar	Manufacturer	Model	Bar mass (kg)	Type
A	ATI tools	AT760B-10	0.83	Cold-rolled steel
B	ATI tools	AT639	0.87	Cold-rolled steel
C	ATI tools	AT692	1.40	Cold-rolled steel
D	Honsa	TBBT760B-10T	1.98	Tungsten alloy
E	Honsa	TBBT639T	2.10	Tungsten alloy
F	Honsa	TBBT692T	2.80	Tungsten alloy
G	Atlas Copco	RBB 04SP-06	1.12	Spring-dampener
H	Atlas Copco	RBB 10SP	1.47	Spring-dampener
I	US industrial tool	TP111R	1.09	Spring-dampener

Table 2

Frequency-weighted and unweighted acceleration means and coefficients of variation (C_v) across all three operators for each bucking bar for the three workplace tasks and the laboratory task. The bars are ranked from lowest to highest weighted acceleration for each task

Rank	Bar	Type	Weighted		Unweighted	
			a_{hv} (ms^{-2})	c_v	a_h (ms^{-2})	C_v
Workplace Task 1						
1	D	Tungsten	6.16	0.11	47.96	0.04
2	E	Tungsten	6.50	0.03	54.62	0.10
3	H	Dampened	6.52	0.21	68.86	0.35
4	G	Dampened	7.00	0.14	52.96	0.19
5	F	Tungsten	7.38	0.14	72.77	0.06
6	I	Dampened	8.07	0.17	215.34	0.18
7	A	Steel	10.40	0.15	108.67	0.15
8	B	Steel	11.25	0.32	124.67	0.20
9	C	Steel	16.52	0.14	162.64	0.13
Workplace Task 2						
1	H	Dampened	4.02	0.17	52.75	0.06
2	E	Tungsten	4.10	0.08	46.12	0.08
3	F	Tungsten	4.94	0.17	66.80	0.17
4	D	Tungsten	5.31	0.27	58.28	0.42
5	C	Steel	7.18	0.10	139.25	0.05
6	G	Dampened	7.32	0.25	64.50	0.04
7	B	Steel	7.43	0.12	89.73	0.08
8	I	Dampened	9.02	0.34	214.56	0.29
9	A	Steel	10.58	0.54	126.57	0.57
Workplace Task 3						
1	E	Tungsten	4.60	0.42	31.15	0.43
2	H	Dampened	5.14	0.23	81.67	0.02
3	D	Tungsten	6.20	0.19	103.46	0.27
4	F	Tungsten	6.76	0.10	95.58	0.27
5	B	Steel	8.36	0.17	68.66	0.18

Rank	**Bar**	**Type**	**Weighted**		**Unweighted**	
			a_{hv} (ms^{-2})	**c_v**	**a_h (ms^{-2})**	**C_v**
6	G	Dampened	8.91	0.18	127.20	0.32
7	C	Steel	9.41	0.09	164.35	0.10
8	I	Dampened	10.92	0.08	301.39	0.09
9	A	Steel	11.31	0.13	200.01	0.12
Lab task						
1	I	Dampened	2.66	0.19	98.44	0.25
2	E	Tungsten	3.27	0.13	42.40	0.11
3	H	Dampened	3.34	0.28	29.25	0.28
4	F	Tungsten	4.03	0.09	54.96	0.08
5	G	Dampened	4.15	0.29	78.49	0.40
6	B	Steel	4.52	0.10	59.79	0.11
7	D	Tungsten	4.53	0.10	59.87	0.11
8	C	Steel	4.84	0.18	82.01	0.18
9	A	Steel	6.00	0.12	116.36	0.12

Table 3

Average ranking of the bucking bars by type for the frequency-weigh ted and unweighted acceleration averages measured in the laboratory and in the workplace

Bar type	**Unweighted**		**Weighted**	
	Avg. rank (1–9)		**Avg. rank (1–9)**	
	Lab	**Work**	**Lab**	**Work**
Steel	6.7	6.6	7.7	7.3
Tungsten	3.3	3.1	4.3	2.8
Dampened	5.0	5.3	3.0	4.9

Table 4

Frequency-weighted and unweighted bucking bar and riveting hammer acceleration means sorted by bucking bar type as measured in the laboratory and in the workplace

Location	Bar type	Weighted ($m\ s^{-2}$)		Unweighted ($m\ s^{-2}$)	
		Bar	Hammer	Bar	Hammer
Lab	Steel	5.1	6.7	86.1	59.6
	Tungsten	3.9	6.8	52.4	59.5
	Dampened	3.4	6.1	68.7	59.4
Workplace	Steel	10.3	6.1	131.6	41.3
	Tungsten	5.8	8.2	64.1	43.9
	Dampened	7.4	9.2	131.0	48.7