Ann. Occup. Hyg., Vol. 52, No. 2, pp. 125–138, 2008
Published by Oxford University Press
on behalf of the British Occupational Hygiene Society
doi:10.1093/annhyg/mem064

An Evaluation of Impact Wrench Vibration Emissions and Test Methods

THOMAS W. McDOWELL*, R. G. DONG, X. XU, D. E. WELCOME and C. WARREN

National Institute for Occupational Safety and Health (NIOSH), NIOSH Health Effects Lab, 1095 Willowdale Road, Morgantown, WV 26505, USA

Received 16 August 2007; in final form 31 October 2007; published online 22 January 2008

In the interest of providing more effective evaluations of impact wrench vibration exposures and the development of improved methods for measuring vibration emissions produced by these tools, this study focused on three variables: acceleration measured at the tool surface, vibration exposure duration per test trial, and the amount of torque required to unseat the nuts following a test trial. For this evaluation, six experienced male impact wrench operators used three samples each of five impact wrench models (four pneumatic models and one battery-powered model) in a simulated work task. The test setup and procedures were based on those provided by an International Organization for Standardization (ISO) Technical Committee overseeing the revision of ISO 8662-7. The work task involved the seating of 10 nuts onto 10 bolts mounted on steel plates. The results indicate that acceleration magnitudes vary not only by tool type but also by individual tools within a type. Thus, evaluators are cautioned against drawing conclusions based on small numbers of tools and/or tool operators. Appropriate sample sizes are suggested. It was further noted that evaluators could draw different conclusions if tool assessments are based on ISO-weighted acceleration as opposed to unweighted acceleration. As expected, vibration exposure durations varied by tool type and by test subject; duration means varied more for study participants than they did for tool types. For the 12 pneumatic tools evaluated in this study, torque varied directly with tool handle acceleration. Therefore, in order to reduce vibration exposure, tools should be selected and adjusted so that they produce no more than the needed torque for the task at hand.

Keywords: exposure assessment; HAVS; impact wrench; vibration

INTRODUCTION

Impact wrenches are widely used in the manufacturing and maintenance of automobiles as well as in other occupational sectors. Operators of these tools are frequently exposed to hand-transmitted vibration (HTV), rotational forces, hand–tool coupling forces, awkward postures and repetitive motions that may lead to occupational injuries or disorders (NIOSH, 1997). Impact wrench use has been specifically associated with the disorder known as vibration white finger (VWF) (see Aiba *et al.*, 1999). Repeated exposures to intensive HTV may lead to VWF and other symptoms commonly associated with hand–arm vibration syndrome (HAVS) (Taylor and Brammer, 1982; Bovenzi, 1998). In the interest of controlling exposures and preventing occupational injuries and disorders, it is important to study the various exposure components and their interactions.

The vibration emitted by tools constitutes one of the primary exposure components to be studied. It is important to characterize vibration emissions in order to provide a clear picture of the exposure signature on the 'dose side' of the dose–response relationship. Vibration characterization is also important for the development of exposure interventions and for improved tool designs. The four primary characteristics of vibration exposure evaluation are vibration frequency, vibration magnitude, exposure duration and cumulative exposure (ISO 5349-1, 2001). There are challenges that complicate the assessment of each of these attributes. Simply measuring the vibration frequencies and magnitudes at the handle of a working tool may not provide an accurate picture of vibration exposures during varying working conditions.

*Author to whom correspondence should be addressed.
Tel: +304-285-6337; fax: +304-285-6265;
e-mail: tmcdowell@cdc.gov

For example, changes in operator posture could affect the hand–arm's biodynamic reaction to the tool vibration along with the tool's vibration exposure signature (Aldien *et al.*, 2005; Dong *et al.*, 2005). Likewise, the gripping and pushing forces applied to the tool handle may also influence the vibration exposure signature (Dong *et al.*, 2004).

Attaining an accurate measure of exposure duration can also be challenging. Exposure durations are typically quantified via reviews of work histories, work observations or employee interviews. These methods are notoriously inaccurate (Peterson *et al.*, 2007). The use of noise or vibration loggers can overcome these inaccuracies (see Teschke *et al.*, 1990' for example), but no standardized method for measuring vibration exposure periods exists. The time component may also need close examination; knowledge of duty cycles and intermittent tool usages may be as important as total exposure duration when characterizing the vibration exposure signature.

In addition to the aforementioned difficulties, there are several other variables that may alter exposure assessment outcomes. The physical characteristics of the tool operator can influence the exposure signature; the elasticity, damping properties and masses of hand and arm tissues can affect tool vibration emissions and the biodynamic responses of a subject's hand–arm system to the vibration inputs (see Chapter 13 of Griffin, 1990). Sources of common measurement errors need to be identified and accounted for. For example, direct current (DC) shifting of vibration signals may lead to exposure overestimations, especially for tools under shock and impact conditions (Dong *et al.*, 2004).

To overcome these difficulties during tool vibration comparisons, it is essential to develop consistent and effective vibration emission assessment techniques such that different impact wrenches can be directly compared and judged based on the same criteria. To that end, the International Organization for Standardization (ISO) established ISO 8662-7 'Hand-Held Portable Power Tools—Measurement of Vibrations at the Handle—Part 7: Wrenches, Screwdrivers, and Nut Runners with Impact, Impulse or Ratchet Action' (1997). In order to provide a consistent and stable load to the tool, a special loading device (braking mechanism) is specified in the standardized test. Unfortunately, such a device may not provide a reasonable simulation of workplace impact wrench operations. The test data obtained from different laboratories may also vary greatly, as measured vibrations have been shown to vary with the subject's physical size and with the magnitude of applied hand forces (Shida *et al.*, 2001). Difficulties in fabricating a durable mechanism that provides consistent tool loading may also contribute to interlaboratory variances.

In view of these problems, ISO Technical Committee 118/SC 3/WG 3—Vibrations in hand-held tools—ad hoc group for wrenches, proposed a new test method to replace the existing method (ISO, 2006). As stated by the committee, the revised setup and procedure are intended to

- more closely simulate actual vibration in the workplace,
- assure that the end results will fall into the top quartile of what is actually experienced by a variety of workers in different work situations,
- produce a vibration result that could be easily translated into risk assessment analysis by the tool user and
- be able to apply the revised procedure to a cross section of all threaded fastener tools from all power sources, including pneumatic, hydraulic or electric (ISO, 2006).

However, this new method has not yet been sufficiently evaluated and tested.

To assist in the development of an improved impact wrench vibration risk assessment standard, the specific aims of this study were to

- identify important characteristics of vibration exposure for users of impact wrenches,
- compare methods for quantifying impact wrench vibrations,
- examine potential influences on vibration measurements,
- investigate how impact wrench vibration emissions, duty cycles and torque measurements vary from tool to tool and subject to subject,
- look into relationships among vibration, exposure duration and torque measures and
- evaluate the proposed impact wrench risk assessment method proposed by the ISO ad hoc group for wrenches (ISO, 2006).

MATERIALS AND METHODS

Experimental setup and procedure

The protocol for this research was reviewed and approved by the National Institute for Occupational Safety and Health (NIOSH) Human Subjects Review Board. In this study, six male impact wrench operators used 15 impact wrenches in a simulated work task. There were four pneumatic models and one battery-powered model; three samples of each tool model were used. All study participants were experienced operators; candidates were asked to have logged at least 100 h with threaded fastener tools. The study apparatus was constructed based on the requirements of the test setup and procedures provided by ISO Technical Committee 118/SC 3/WG 3 (ISO, 2006).

The test setup is depicted in Fig. 1. Briefly, the test apparatus consists of two removable 38-mm thick

Fig. 1. (a) The impact wrench test setup consisting of two removable steel plates vertically mounted on a concrete block. Each plate accommodates 10 M20 × 60 mm Grade 8 bolts. A test trial comprises the seating of 10 nuts onto one of the sets of 10 bolts in a 30-s period. The subject alternates between plates for a total of five 30-s trials per tool. (b) Nuts and washers are shown in their initial positions.

hardened steel plates vertically mounted on a concrete block. Each plate was fabricated with channels and holes to accommodate 10 M20 × 60 mm Grade 8 steel bolts. The 10 bolts on each plate are arranged in two evenly spaced rows of five bolts each (see Fig. 1a). Each bolt is fitted with a nut, two Bellville washers (20.4 mm ID, 40 mm OD) stacked in parallel along with a matching flat washer (see Fig. 1b). In an effort to obtain vibration emission values that correspond to values that workers would be expected to experience in actual work situations, the revised procedure calls for vibration measurements to be made over the course of a series of 30-s trials that involve the seating of 10 nuts onto the plate-mounted studs or bolts. To be consistent with the vibration measurement method specified in the ISO vibration risk assessment standard (ISO 5349-1, 2001), another proposed major change to ISO 8662-7 (1997) is that vibrations are to be measured in three axes instead of a single axis as is specified in the existing standard.

In the current study, two complete sets of new bolts, washers and nuts were used during the tests. As specified above, a test trial consisted of the seating of 10 nuts on one of the steel plates in a 30-s period. In order to control the pace of the experiment, a custom program using National Instruments LabVIEW™ software was developed. Basically, the program's display consisted of 10 dial gauges that represented the 10 nuts to be tightened during a trial. The dial needle swept around a gauge in 2 s, then the subject was prompted to move to the next nut; 1 s later, the needle swept around the next gauge, and so on. The pacing program ran on a notebook computer that was placed in front of the test subject. Each participant completed practice runs to become accustomed to the work task and pacing program. This pacing mechanism proved to be successful as trials during the tests were consistently within 30 ± 1.5 s for all study participants. After a 10-nut trial, the subject rested while a test engineer backed-off the nuts to their starting positions. The subject was then prompted to complete the next trial on the alternate plate. In this fashion, about half of a test session's trials were completed on one plate and half on the other.

Each subject completed five, 10-nut trials with each of the 15 tools for a total of 75 trials in a test session. All tools were in good working order and had only been used in round-robin laboratory testing using this same test fixture and procedure. Five tool models with three samples each were used:

1. Tools A1-3: Ingersoll-Rand 2135Ti, max torque = 848 Nm, weight = 1.8 kg
2. Tools B1-3: Atlas Copco EP12PTS150-HR13-AT, max torque = 150 Nm, weight = 2.5 kg
3. Tools C1-3: Chicago Pneumatic CP749, max torque = 612 Nm, weight = 2.4 kg
4. Tools D1-3: Chicago Pneumatic CP7733, max torque = 746 Nm, weight = 2.5 kg
5. Tools E1-3: Makita BTW120, max torque = 120 Nm, weight = 1.6 kg

The first four listed tool models are pneumatic tools. For these tool models, the supplied air pressure was regulated to 689 kPa (100 psi). The Makita model is a battery-powered tool. The 12V battery packs for each of the three Makita tools were fully charged at the beginning of each test session. The testing order of the 15 tools was independently randomized for each subject.

According to the proposed revisions to the standard, when possible, vibrations are to be measured at two locations on the tool, either at both handles where supplied or at other locations where the user is likely to grip and support the tool (ISO, 2006). None of the tools used in this study are equipped with secondary handles. For the four pneumatic tools, vibration was measured at the tool handle and at the front portion of the tool housing. For the smaller,

battery-powered tool, only handle vibration was measured. All vibration measurements were collected via calibrated PCB Model 356B11 triaxial accelerometers. Each accelerometer was mounted on an aluminum mounting block. Hose clamps were used to secure the accelerometer assemblies to the tools.

The measurement of vibration of percussive tools often yields significant DC shifts in the piezoelectric accelerometer output (Kitchener, 1977). During practice runs, evidence of such DC shifts in some of the measurements—especially those on the tool housings of the Chicago Pneumatic and Ingersoll-Rand models—were observed. In order to alleviate this DC shifting problem, thin layers of rubber were placed underneath the accelerometer mounting blocks and hose clamps to provide mechanical filtering in a similar fashion to that detailed in another study (Dong *et al.*, 2004). This filtering method proved to be effective at eliminating the DC shifts. Figure 2 shows the typical arrangement for the accelerometers, mounting blocks, hose clamps, and layers of rubber.

Vibration data were collected for each one-third octave band with center frequencies from 6.3 to 1250 Hz. The triaxial accelerometer signals were conditioned via PCB 480E09 ICP sensor signal conditioners with gains set to '1' (no amplification). The vibration signals were then fed into a portable six-channel B&K PULSE system (Model 3032A) where a separate text file was generated for each test trial. A Microsoft Excel spreadsheet was used to process the weighted accelerations at the tool handle and at the tool housing (where applicable) for each 30-s trial. Immediately following each five-trial tool run, the coefficient of variation (CV) of the root-sum-of-squares value (total value) for the five consecutive trials was calculated. Trials were repeated if the CV was $\geq$0.15. Processed vibration values proved to be reasonably consistent as <5% of all test trials required replication.

Study variables

This study focused primarily on three outcome variables: vibration magnitude, vibration exposure duration and torque. Vibration data were collected in three axes via triaxial accelerometers as described above. Vibration magnitude root-mean-square (r.m.s.) values were determined for each one-third octave band from 6.3 to 1250 Hz for each axis. The 'total' value for each triaxial accelerometer was then calculated using the following formula:

$$a_{\text{total}} = \sqrt{a_x^2 + a_y^2 + a_z^2}, \qquad (1)$$

where a_{total} is the unweighted root-sum-of-squares total value and a_x, a_y and a_z are the unweighted r.m.s. values for the x-, y- and z-axis, respectively. (Refer to Fig. 2 to see the reference coordinate system.) In similar fashion, the ISO-weighted root-sum-of-squares vibration magnitude total values were calculated after applying the one-third octave band weighting coefficients presented in ISO 5349-1 (2001). In this fashion, ISO-weighted and unweighted vibration magnitudes were quantified for two tool locations (handle and housing) for each trial. All vibration magnitude values are expressed in m s^{-2}.

As described above, vibration data were collected throughout the entire 30-s trial as the subject moved from nut to nut. Naturally, these measurements included periods when the tool was not operating; thus, the measurement period included times when the operator was not being exposed to tool vibration. It was hypothesized that actual exposure time would vary by tool and by subject. An algorithm was developed to aid in the assessment of these exposure duration variations. Time-domain tool vibration spectra were

Fig. 2. (a) Typical arrangement of the accelerometers, mounting blocks and hose clamps used for mounting the two accelerometers on the tools. For the four pneumatic tool models, measurements were taken at the tool handles and near the front of the tool housing. For the battery tool model, only handle measurements were collected. (b) Layers of rubber were placed under the hose clamp and accelerometer mounts to prevent DC shifting of the acceleration measurements.

collected, and the three-axes (total) vibration waveforms were rectified and digitally processed to quantify the amount of tool vibration exposure time for each trial. Basically, a threshold value for vibration exposure was established, and periods when vibration exceeded the threshold were considered to be tool vibration exposure time. Figure 3 shows a sample output of this algorithm applied to three nuts during a typical trial. The intratrial exposure times were summed to provide a measure of total exposure time for each trial; these values were then used to examine relationships among exposure times, tools and subjects.

Nut static torque measurements were collected for just one of the subjects. A click-type torque wrench was used to measure the amount of torque required to unseat each nut after each of four, 10-nut trials. These torque measurements were taken for each of the 12 pneumatic tools; nut torque measurements were not obtained for the three battery-powered tools because the torque produced by those tools is below that of the operating range of the torque wrench used in this study.

Data processing and statistical analysis

Where appropriate, univariate general linear model analysis of variance (ANOVA) tests were performed to identify significant study factors. Also where appropriate, Tukey's honestly significant difference (HSD) *post hoc* pairwise comparisons were performed. All ANOVAs and Tukey's HSD tests were performed using SPSS statistical software (SPSS Inc., version 14.0). Regression/correlation analyses were performed using Microsoft Excel. Analysis results were considered significant at the $P < 0.05$ level.

RESULTS

Vibration

Naturally, each tool type produced its own vibration signature. Representative unweighted vibration spectra measured at the tool handles are presented in Fig. 4. Figure 5 illustrates acceleration variability for each tool and how these measurement

Fig. 3. Exposure duration algorithm output for the seating of the first three nuts in a typical 10-nut trial. Tool handle vibration signals were rectified, an exposure threshold was established and time periods where tool handle vibration exceeded the threshold were summed to quantify the actual exposure time during each 30-s trial.

Fig. 4. Typical unweighted r.m.s. vibration spectra measured at the handles of each of the five tool types.

Fig. 5. Distributions of (a) unweighted and (b) ISO-weighted total r.m.s. vibration values measured at the handle of each tool by all six subjects ($n = 30$). The boxes represent the interquartile range for each distribution; the line within each box is the median value. The whiskers extend to the 5th and 95th percentiles.

distributions varied among the 15 tools. As can be seen, the distributions within each tool model are fairly similar for both weighted and ISO-weighted acceleration values. It is clear that vibration magnitudes for the Type B tools are considerably lower than those for the other four tool models. Further, there is less overall variability with the acceleration measurements for the Type B tools. In similar fashion, the distributions of tool handle acceleration values for each of the six study participants are shown in Fig. 6.

As denoted in Table 1, the ANOVA results revealed that both tool and test subject are significant influences on tool vibration. The tool/subject interaction is also significant. As indicated, the conclusions drawn from the ANOVA results were the same whether unweighted or ISO-weighted acceleration values were used in the analysis. Likewise, tool handle and tool housing measurements yielded the same conclusions. These similarities are further displayed in Fig. 7 where tool handle and tool housing acceleration measurements are compared for both ISO-weighted

Fig. 6. Distributions of (a) unweighted and (b) ISO-weighted total r.m.s. vibration values measured at all 15 tool handles for each study participant (n = 75). The boxes represent the interquartile range for each distribution; the line within each box is the median value. The whiskers extend to the 5th and 95th percentiles.

and unweighted values. As shown in the figure, the Pearson R-squared values are statistically significant, while the slopes of the trend lines for both cases approach unity.

Post hoc pairwise comparisons of means of tool handle acceleration measurements for the test subjects and tools are contained in Tables 2 and 3, respectively. Overall, Subjects T and D exhibited higher vibration exposure magnitudes than the other subjects. As indicated in Table 3, for unweighted vibrations, the Type A tools were significantly higher than the other tool types. However, when ISO frequency weighting is applied, the Type C tools move to the top. This characteristic is further indicated in Table 4; this table contains means and standard deviations of tool handle acceleration measurements for each test subject and tool type. The tool type and test subject interaction is also revealed in Table 4; the rank order of the subject's exposures varies with tool type. The pattern of variation differs depending on whether ISO-weighted or unweighted accelerations are used in the analysis.

Exposure duration

The ANOVA results for exposure duration per 30-s test trial are contained in Table 5. As was the case for tool acceleration, vibration exposure duration also depended on test subject and tool type. Likewise, the test subject/tool type interaction was significant. *Post hoc* pairwise comparisons for test subject and tool type are displayed, respectively, in Tables 6 and 7. As was the case for vibration magnitude, Subjects T and D had significantly higher exposure times than the other four subjects. There were only two subsets among tool types for exposure duration;

Table 1. ANOVA tables for unweighted and ISO-weighted r.m.s. acceleration values measured at the tool handles of each of the 15 tools and at the housings of the 12 pneumatic tools

Dependent variable	Source	SS	df	MS	F	P
Unweighted handle vibration	Tool	1 802 882.7	14	128 777.3	1265.5	<0.001*
	Subject	73 243.0	5	14 648.6	144.0	<0.001*
	Tool × subject	148 739.7	70	2124.9	20.9	<0.001*
	Error	36 632.2	360	101.8	—	—
Weighted handle vibration	Tool	1943.7	14	245.6	827.5	<0.001*
	Subject	165.6	5	33.1	111.6	<0.001*
	Tool × subject	218.4	70	3.1	10.5	<0.001*
	Error	106.8	360	0.3	—	—
Unweighted handle vibration	Tool	1 575 199.1	11	143 199.9	2222.6	<0.001*
	Subject	113 897.0	5	22 779.4	353.6	<0.001*
	Tool × subject	99 389.8	55	1807.1	28.0	<0.001*
	Error	18 555.8	288	64.4	—	—
Weighted handle vibration	Tool	2376.9	11	216.1	790.6	<0.001*
	Subject	186.7	5	37.3	136.6	<0.001*
	Tool × subject	253.7	55	4.6	16.9	<0.001*
	Error	78.7	288	0.3	—	—

Fig. 7. Correlations between tool handle and tool housing unweighted and ISO-weighted r.m.s. acceleration measurements for the 12 pneumatic impact wrenches ($n = 360$). In both cases, the R-squared values are statistically significant ($P < 0.001$).

tool type D durations were significantly longer than Types A, B and E; no other significant differences were observed.

The distributions of exposure duration times are illustrated in Figs 8 and 9. Figure 8 displays the distributions for each of the five tool types. As shown in the figure, tool types B and E exhibited considerably less overall variability than the other three tool types. The distribution of duration times for each subject is shown in Fig. 9. The median values for Subjects D and T are clearly higher than the other four subjects. Subject D also displayed much more variability than the other five study participants.

The measured acceleration magnitude is the r.m.s. value averaged over the 30-s trial. If the average vibration exposure duration per nut is longer, the measured acceleration magnitude could also be higher, although the average acceleration level during the exposure period could remain unchanged. Therefore, exposure duration and acceleration magnitude may have some association. To evaluate this association, regression analysis between these two factors was

performed, which revealed that they are reliably correlated ($R^2 = 0.12$, $P < 0.001$).

Torque

As detailed earlier, for one of the study participants, the amount of torque required to unseat each nut was measured after four 10-nut trials with each of the 12 pneumatic tools. An ANOVA was performed; tool, nut and the tool/nut interaction were all found to be significant factors. The ANOVA results are contained in Table 8. The distributions of torque measurements for each pneumatic tool type are displayed in Fig. 10. As the boxplots show, the torque required to unseat the nuts tightened with the Type B tools was considerably lower than the torque required for the other three tool models. Furthermore, the range of torque measurements for the Type B tools was less than those for the other tools. *Post hoc* tests indicate that the torque values for Nuts 5, 8 and 12 are significantly lower than those for the other nuts ($P < 0.05$).

The relationship between the measured torque and the amount of vibration produced by each pneumatic tool was examined. That significant correlation is illustrated in Fig. 11. As shown, measured torque increases with ISO-weighted acceleration.

Table 2. Tukey's HSD *post hoc* pairwise comparison results for unweighted and ISO-weighted tool handle r.m.s. acceleration means for the six study participants ($n = 75$)

	Test subject					
	M	W	Q	S	D	T
Unweighted vibration						
Mean (m s^{-2})	126.5	127.4	133.1	133.2	153.9	158.9
ISO-weighted vibration						
Mean (m s^{-2})	6.0	6.0	6.5	6.5	7.1	7.7

Each line represents means that are not significantly different ($P > 0.05$). Means that do differ significantly ($P < 0.05$) are not subsumed under a line.

DISCUSSION AND CONCLUSIONS

This study examined various parameters that are commonly associated with risk assessments of HTV exposures to operators of impact wrenches. The test setup and procedure were developed by an ISO ad hoc group for impact wrenches for the proposed revision of ISO 8662-7 (1997). The study focused on three primary variables: acceleration measured at the tool surface, vibration exposure duration per test trial, and the amount of torque required to unseat nuts after they were tightened during a test trial. The results for each of these variables are discussed below.

Vibration

The average ISO-weighted acceleration measured at the handles of the tools examined in this study was 6.6 m s^{-2}. This level of vibration is comparable to that reported for impact wrenches examined in other studies (e.g. Griffin, 1997; Aiba *et al.*, 1999). To stay below the Action Level published in the 2002 European Union Directive (EU, 2002), a tool operator would be allowed to operate the average tool for a little over 1 h (based on an 8-h reference period). To remain below the Directive's Exposure Limit Value, the daily operation would have to be limited to ~4.5 h.

As expected, the acceleration magnitude varied by tool model. Perhaps more important, the acceleration magnitude also varied by tool within a specific tool model. Only one tool model, Type B, did not exhibit significant acceleration differences among the three-tool samples used in this study. For the three Type C tools, each of the individual unweighted acceleration means was significantly different than the other two. This indicates that it is necessary to include at least three, and possibly more, tools per model in impact wrench vibration exposure assessments if one is using the assessment to quantify exposures for a specific tool model or when comparing exposure levels of different tool models.

Similar variations were observed when examining the test subject vibration exposures; acceleration

Table 3. Tukey's HSD *post hoc* pairwise comparison results for unweighted and ISO-weighted r.m.s. acceleration means measured at the handles of the 15 tools (n = 30)

	Tool														
Unweighted vibration	B2	B3	B1	D2	D3	D1	C2	E1	C1	E2	E3	C3	A2	A3	A1
Mean (m s^{-2})	27.5	30.0	31.9	110.3	122.6	122.9	146.9	151.0	160.3	170.8	178.4	184.0	205.4	212.8	227.5
ISO-weighted vibration	B2	B3	B1	D2	D3	D1	E1	E2	E3	A2	A3	C1	A1	C2	C3
Mean (m s^{-2})	2.9	2.9	2.9	6.5	6.5	6.5	6.5	7.2	7.3	7.5	7.7	8.2	8.3	8.5	10.0

Each line represents means that are not significantly different ($P > 0.05$). Means that do differ significantly ($P < 0.05$) are not subsumed under a line.

Table 4. Tool handle total r.m.s. acceleration means and standard deviations (SDs) for each test subject (n = 15) and tool type (n = 90)

Test subject	Type B		Type D		Type E		Type A		Type C	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
ISO-weighted acceleration (m s^{-2})										
Q	2.6	0.3	6.4	0.8	6.5	0.5	8.2	1.4	8.9	2.5
W	2.7	0.1	6.0	0.4	6.6	0.6	6.8	0.6	7.9	0.7
M	2.7	0.2	5.5	0.5	7.1	0.3	6.5	0.3	8.0	1.0
T	3.0	0.2	7.6	0.5	8.3	0.8	9.9	0.8	9.7	0.7
S	3.2	0.3	6.3	0.3	6.4	0.8	7.7	0.1	8.8	0.8
D	3.2	0.5	7.1	0.7	7.3	0.8	7.7	0.7	10.3	1.5
Average	2.9	0.3	6.5	0.5	7.0	0.6	7.8	0.6	8.9	1.2
Unweighted acceleration (m s^{-2})										
Q	30.1	6.4	109.0	20.4	145.6	14.9	219.0	34.4	161.6	37.8
W	26.4	1.5	114.0	10.4	153.0	16.4	209.6	10.8	134.1	17.6
M	27.0	3.3	100.6	9.3	202.4	3.3	173.5	10.0	129.2	6.8
T	29.2	1.9	130.5	3.8	191.1	26.6	251.6	20.9	192.2	18.9
S	35.3	1.9	119.0	5.8	147.3	21.1	209.0	5.9	155.5	15.7
D	30.8	1.6	138.5	3.2	161.1	15.4	228.7	11.2	210.4	32.3
Average	29.8	2.8	118.6	8.8	166.7	16.3	215.2	15.5	163.8	21.5

Table 5. ANOVA table for vibration exposure duration per 30-s test trial measured at the tool handles

Source	SS	df	MS	F	P
Subject	361.9	5	72.4	21.3	<0.001*
Tool type	63.6	4	15.9	4.7	<0.003*
Subject × type	241.9	20	12.1	3.6	<0.001*
Error	204.3	60	3.4	—	—

Table 6. Tukey's HSD *post hoc* pairwise comparison results for vibration exposure duration per 30-s test trial for the six study participants (n = 75)

Exposure duration	Test subject					
	M	Q	W	S	T	D
Mean (s)	6.5	7.8	8.2	8.6	11.2	12.3

Each line represents means that are not significantly different ($P > 0.05$). Means that do differ significantly ($P < 0.05$) are not subsumed under a line.

Table 7. Tukey's HSD *post hoc* pairwise comparison results for vibration exposure duration per 30-s test trial for the five tool types (n = 90)

Exposure Duration	Tool type				
	B	E	A	C	D
Mean (s)	8.2	8.6	8.7	9.3	10.6

Each line represents means that are not significantly different ($P > 0.05$). Means that do differ significantly ($P < 0.05$) are not subsumed under a line.

Fig. 8. Distributions of vibration exposure duration values for the 30-s trials for each of the five impact wrench models tested by all six study participants (n = 90). The boxes represent the interquartile range for each distribution; the line within each box is the median value. The whiskers extend to the 5th and 95th percentiles.

values varied considerably among and within study participants. Comparing Figs 5 and 6, it can be seen that the within-subject distribution ranges for measured acceleration were broader for test subjects than the within-tool ranges. As indicated in Table 3, the six test subject acceleration means can be partitioned into three significantly different subsets. These results indicate that a sample of only three test subjects may be insufficient for accurately predicting vibration exposure magnitudes produced by impact wrenches.

To further examine these study design issues, we applied non-centrality operating characteristic curves to determine appropriate sample sizes (see Montgomery, 2001). Basically, the experimental design can be optimized by selecting a desired

Fig. 9. Distributions of vibration exposure duration values for the 30-s trials for each of the six study participants ($n = 75$). The boxes represent the interquartile range for each distribution; the line within each box is the median value. The whiskers extend to the 5th and 95th percentiles.

Table 8. ANOVA table for torque required to unseat the nuts tightened by one of the test subjects using the 12 pneumatic tools

Source	SS	df	MS	F	P
Tool	2 680 607.2	11	91 891.0	596.5	<0.001*
Nut	192 328.3	19	10 122.5	65.7	<0.001*
Tool × nut	125 420.3	209	600.1	3.9	<0.001*
Error	36 973.8	240	154.1	—	—

Fig. 10. Distributions of the measured torque required to unseat nuts tightened by one of the subjects using each of the four pneumatic tool models ($n = 120$). The boxes represent the interquartile range for each distribution; the line within each box is the median value. The whiskers extend to the 5th and 95th percentiles.

sensitivity and acceptable Type I (α) and Type II (β) error risk probabilities, and then varying the number of levels for the fixed factors (i.e. the number of tool operators, the number of tool models and/or the number of tools per model) along with the number of replicates per combination. For this evaluation, a sensitivity of 0.5 m s^{-2} ISO-weighted acceleration was desired, the number of replicates was fixed at five, α was set at 0.05 and β was set at 0.20. Based on the variance of ISO-weighted acceleration observed in this study, in order to reliably rank five different tool models using the prescribed procedure, at least five tool operators would be required to achieve the desired sensitivity while limiting the Type I and II error risk probabilities. If the number of tools per model was increased to four, only four tool operators would be needed. In order to run the experiment with only three tool operators, the number of tools per model would have to be increased to five. Obviously, increasing the number of tools in the assessment dramatically increases the size of the experimental matrix; it may be more desirable to run the experiment using more tool operators.

Fig. 11. Relationship between ISO-weighted r.m.s. acceleration measured at the tool handles of the 12 pneumatic tools and the torque required to unseat the nuts tightened by those tools. The R-squared value is statistically significant ($P < 0.001$).

These findings contradict the current ISO standard (ISO 8662-7, 1997) as well the proposed changes to that standard (ISO, 2006), both of which call for testing by just three skilled operators and three tools per model. Furthermore, as indicated in Table 1, there is a significant interaction between tool and test subject. This interaction effect is demonstrated in Table 4; there is little consistency in the rank orders of acceleration means for the test subjects across the tool models. This further indicates that three test subjects may be inadequate for a reliable assessment.

Much of this variability is likely due to differences in applied hand forces, postures, and biodynamic responses of the hand–arm system (Griffin, 1997; Shida *et al.*, 2001). None of these factors were measured or controlled in this study. Even skilled operators will individually adjust to tool design and work task differences. Perhaps the influence of these individual differences could be partially countered by controlling applied forces and standardizing postures. In that case, it might be possible to conduct accurate assessments using only three test subjects.

However, controlling hand forces and work postures can present considerable challenges during laboratory and field-testing. Moreover, specifying the applied forces and work postures during assessments may yield results that are not representative of those found in actual workplace environments. Therefore, increasing the number of subjects for a more reliable comparison may be a better solution.

As indicated in Table 1, ANOVA results were the same for tool handle and tool housing acceleration measurements. These similarities are also reflected in Fig. 7. These results imply that accelerometer location may not be critical for impact wrench exposure assessments—especially if one simply wants to compare the vibration emissions of various tool models. For such comparisons, it may be best to select accelerometer mounting locations that allow for minimal interference with the hand–tool interface. However, the evaluator should be consistent with accelerometer placement, and it seems logical to collect vibration data at a point close to where HTV enters the workers' hand–arm system. In any case, accelerometer placement should always be reported.

When comparing unweighted and ISO-weighted accelerations in this study, many of the conclusions would be the same. For example, as displayed in Table 1, the ANOVA results are the same for ISO-weighted and unweighted acceleration values. Likewise, the pairwise comparisons contained in Table 3 yielded identical test subject subsets. However, as indicated in Tables 2 and 4, ISO weighting does affect tool acceleration comparisons. As shown in Fig. 4, the Model A tools exhibit a more pronounced high-frequency component as compared to the other four tool models. This component is a major contributor to that model's unweighted acceleration values. These high-frequency constituents are suppressed through the application of ISO weighting, and as a result, the Model C tools rise to the top of the acceleration rank order. As displayed in Table 2, another result of the weighting application is the formation of larger pairwise comparison subsets. The appropriateness of the current ISO weighting has been discussed for several years (e.g. Wasserman, 1989). This debate will likely continue for some time. Until consensus is reached, it may be useful for researchers to report both unweighted and ISO-weighted findings.

Exposure duration

It was not surprising to find that exposure duration depends on tool and test subject. The tool models evaluated in this study were not necessarily designed to perform the same work tasks; the simulated work task employed in this study may not be representative of the tasks that each specific tool was designed for. This is one of several reasons that vibration exposure duration differences are to be expected. Likewise, even though all study participants were experienced impact wrench users, they came from different work backgrounds, and this particular study design likely matches some subjects' experiences better than others. Furthermore, differences in task training and work experience will certainly lead to variability in posture and other task performance characteristics that will, in turn, result in exposure duration differences.

Duration means varied more for test subjects than for tool types; the means for study participants ranged from 6.5 to 12.3 s, while the range for tool types ranged from 8.2 to 10.6 s. Moreover, pairwise comparisons yielded three subsets for test subjects and only two subsets for tool types. Based on these results, workers may be expected to exhibit more exposure duration variability than do tools. As outlined previously, the simulated work task in the present study utilized a pacing program to control trial times. Obviously, in actual work tasks, such pacing mechanisms do not normally exist, and in these real-world cases, vibration exposure duration measurements would likely exhibit even more variability.

Torque

The measurement of the amount of torque required to unseat the nuts after a test trial is a time-consuming process; the inclusion of this metric dramatically increased the time of the tool evaluation. Therefore, due to time constraints, torque measurements were only collected for one of the study participants. However, even this limited information produced some interesting results. As indicated in Table 8, the amount of torque depended on which tool was being used and which nut was being tightened. The interaction of these two factors was also statistically significant. Figure 10 shows how torque varied by tool. As illustrated in the figure, the Model B tools produced consistently low torque. While not shown in any figure, the Model B tools were also the primary reason for the tool/nut interaction. The significant nut-to-nut torque variations observed in this study were not evident with the three Model B tools, while the torque values for the individual nuts varied significantly for the other three pneumatic tool models.

An examination of the torque values for the individual nuts reveals three nuts with consistently lower torque values. These significantly lower means are likely due to physical differences among the nuts and/or bolts. This phenomenon may be a reflection of manufacturing differences in the hardware, or due to dissimilar wear patterns or damage that may have resulted from irregular tool actions (e.g. tool misalignment). It is interesting to note that the two highest torque averages are those for Nuts 10 and 20—the final nuts in each 10-nut set. This potential sequence effect may need further examination. In any case, it is evident that nut and bolt differences may introduce variability in torque measurements, and the evaluator should be aware of these potential influences.

Figure 11 shows the relationship between torque and ISO-weighted vibration. Clearly, vibration increases with torque for these 12 pneumatic tools. While not displayed, this relationship also exists with unweighted vibration, although the R-squared value is slightly lower ($R^2 = 0.79$, $P < 0.001$). This relationship indicates that there may be a trade-off between torque and vibration exposure. This may have tool selection implications; it is probably best to choose tools that deliver no more than the torque required to satisfactorily complete the work task. Oversizing tools may unnecessarily expose workers to excessive vibration.

If the objective of an evaluation is to compare different tool models built for similar work tasks, static torque measurements may provide useful information. Dynamic torque measurements may also contribute valuable data for such comparative evaluations. For the present study, all tools were operated at their highest torque settings, but it should be noted again that the tool models evaluated were not necessarily designed to perform the same work tasks. So in this case, comparing tool models using static torque measurements may not be appropriate.

Other observations

It is generally recognized that work posture and applied hand forces can significantly affect HTV exposure. In light of these observations, it may be useful to modify the impact wrench test procedure to reduce variability in the results. For example, in order to better control work posture, the operator could stand on a platform with adjustable height. Thus, elbow and shoulder angles could be more standardized. In order to evaluate the influence of applied forces, a force plate could be added to the platform to measure ground reaction forces. Grip forces could be estimated using a force-recall technique similar to that used in earlier studies (McDowell *et al.*, 2006, 2007).

While this test rig is suitable for work task simulations using the majority of impact wrench models, it may not be appropriate for larger tool models; it may be too difficult to maneuver large tools from one nut to another in the prescribed time frame. For larger tools, the apparatus may have to be modified to include some sort of tool suspension system.

While it is recognized that this test apparatus cannot provide reasonable simulations for all work tasks involving impact wrenches, the apparatus and test procedure seem to generate appropriate data for tool screening for a wide variety of impact wrench models and many common workplace operations.

Disclaimer—The findings and conclusions in this article have not been formally disseminated by the NIOSH and should not be construed to represent any agency determination or policy. The mention of trade names, commercial products or organizations does not imply endorsement by the US Government.

REFERENCES

Aiba Y, Ohshiba S, Ishizuka H *et al.* (1999) A study on the effects of countermeasures for vibrating tool workers using an impact wrench. Ind Health; 37: 426–31.

Aldien Y, Marcotte P, Rakheja S *et al.* (2005) Mechanical impedance and absorbed power of hand-arm under xh-axis vibration and role of hand forces and posture. Ind Health; 43: 495–508.

Bovenzi M. (1998) Exposure-response relationship in the hand-arm vibration syndrome: an overview of current epidemiology research. Int Arch Occup Environ Health; 71: 509–19.

Dong RG, McDowell TW, Welcome DE. (2005) Biodynamic response at the palm of the human hand subjected to a random vibration. Ind Health; 43: 241–55.

Dong RG, McDowell TW, Welcome DE *et al.* (2004) An evaluation of the standardized chipping hammer test specified in ISO 8662-2, 1992. Ann Occup Hyg; 48: 39–49.

EU. (2002) Directive 2002/44/EC of the European Parliament and the Council of 25 June 2002 on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (vibration) (sixteenth individual directive within the meaning of Article 16(1) of Directive 89/391/EEC). Luxembourg: The European Parliament and the Council of the European Union (EU).

Griffin MJ. (1990) Handbook of human vibration. London: Academic Press.

Griffin MJ. (1997) Measurement, evaluation, and assessment of occupational exposures to hand-transmitted vibration. Occup Environ Med; 54: 73–89.

ISO. (1997) ISO 8662-7: Hand-held portable power tools—measurement of vibrations at the handle—part 7: wrenches, screwdrivers, and nut runners with impact, impulse, or ratchet action. Reference No. ISO 8662-7:1997(E). Geneva, Switzerland: International Organization for Standardization.

ISO. (2001) ISO 5349-1: Mechanical vibration—measurement and evaluation of human exposure to hand-transmitted vibration—part 1: general requirements. Reference No. ISO 5349-1:2001. Geneva, Switzerland: International Organization for Standardization.

ISO. (2006) Round robin test setup and procedure for proposed changes to ISO 8662-7. ISO/TC 118/SC 3/WG 3—vibrations in hand-held tools—ad hoc group for wrenches.

Kitchener R. (1977) The measurement of hand-arm vibration in industry. 2nd international occupational hand-arm vibration conference, DHHS (NIOSH), Publication No. 77-170. Cincinnati, OH: National Institute for Occupational Safety & Health; pp. 153–9.

McDowell TW, Wiker SF, Dong RG *et al.* (2006) Evaluation of psychometric estimates of vibratory hand-tool grip and push forces. Int J Ind Ergon; 36: 119–28.

McDowell TW, Wiker SF, Dong RG *et al.* (2007) Effects of vibration on grip and push force-recall performance. Int J Ind Ergon; 37: 257–66.

Montgomery DC. (2001) Design and analysis of experiments. 5th edn. New York: John Wiley & Sons.

NIOSH. (1997) Musculoskeletal disorders and workplace factors: a critical review of epidemiologic evidence for work-related musculoskeletal disorders of the neck, upper extremity, and low back, NIOSH publication. Cincinnati, OH: US Department of Health and Human Services, National Institute for Occupational Safety and Health; pp. 97–141.

Peterson DR, Brammer AJ, Cherniack MG. (2007) Long-duration vibration and grip force measurements using a custom-built data logger and palm-mounted sensors. In: Bovenzi M, Peretti A, Nataletti P and Moschioni G, editors. Proceedings of the 11th international conference on hand-arm vibration. Bologna, Italy: Associazione Italiana di Acustica; pp. 583–8.

Shida Y, Nakagawa Y, Okuno M *et al*. (2001) A comparison of vibration magnitudes on the tool with different subject according to the ISO 8662-7 standard. Ind Health; 39: 255–68.

Taylor W, Brammer AJ. (1982) Vibration effects on the hand and arm in industry: an introduction and review. In: Brammer AJ and Taylor W, editors. Vibration effects on the hand and arm in industry. New York: John Wiley & Sons.

Teschke K, Brubaker RL, Morrison BJ. (1990) Using noise exposure histories to quantify duration of vibration exposure in tree fallers. AIHAJ; 51: 485–93.

Wasserman DE. (1989) To weight or not to weight—that is the question. J Occup Med; 31: 909.