International Journal of Industrial Ergonomics 39 (2009) 174–184

Contents lists available at ScienceDirect

International Journal of Industrial Ergonomics

journal homepage: www.elsevier.com/locate/ergon

An investigation on characteristics of the vibration transmitted to wrist and elbow in the operation of impact wrenches

X.S. Xu*, D.E. Welcome, T.W. McDowell, C. Warren, R.G. Dong

Engineering & Control Technology Branch, National Institute for Occupational Safety and Health, 1095 Willowdale Road, Morgantown, WV 26505, USA

ARTICLE INFO

Article history:
Received 15 October 2007
Received in revised form 11 April 2008
Accepted 8 May 2008
Available online 3 August 2008

Keywords:
Hand-arm vibration
Hand-transmitted vibration
Impact wrench
Nut runner
Wrist

ABSTRACT

To help assess the risk of the vibration exposure during impact wrench operation and to develop a convenient and effective method to monitor and control the exposure, this study aims to investigate the characteristics of the vibrations transmitted to the wrist and elbow in the operation and to evaluate the on-the-wrist and on-the-elbow vibration measurement methods. Six subjects participated in the experiment. Each of them used 15 impact wrenches on a simulated workstation. Tri-axial accelerations at three locations (tool handle, wrist, and elbow) and the tool effective torques were measured and used in the evaluations. Results confirm that the severity of the vibration exposure generally depends on tool and individual, and that the vibrations measured at wrist and elbow reflect the influences of both factors. This study also found that the accelerations measured at the wrist and elbow are correlated with the ISO frequency-weighted tool acceleration. The fundamental resonance of the hand-arm system in the range of 16–50 Hz is well reflected in the vibration measured at the wrist. The results also demonstrate that vibration exposure duration can be reliably detected from the wrist vibration data. Moreover, the wrist vibration is suggestively correlated with the torque of the pneumatic impact wrenches. These findings suggest that the measurement of the wrist vibration can be used as an alternative approach to perform the exposure risk assessment and to monitor and control the exposures in the operation of the impact wrenches.

Relevance to Industry: Impact wrenches or nut runners with impact action are widely and intensively used in automobile manufacturing and repair, which could generate significant vibration and require forceful actions. Prolonged, intensive exposure to both vibration and forceful actions could result in hand-arm vibration syndrome and carpal tunnel syndrome. The results of this study suggest that the on-the-wrist vibration measurement is a reasonable alternative approach for quantifying and assessing the exposures, which provides a theoretical base for developing a convenient and effective method for monitoring and controlling the combined exposures. The results of this study also suggest that the on-the-wrist method can also be used at workplaces to perform screening tests of the tools with dominant vibration frequencies similar to those of the impact wrenches and to evaluate the effectiveness of the anti-vibration devices used with such tools.

Published by Elsevier B.V.

1. Introduction

Various impact wrenches or nut runners with impact action are widely and intensively used in automobile manufacturing and repair (Van Bergeijk, 1987; Kihlberg et al., 1995). The operations of such tools expose workers to vibration and the repetitive forces necessary to hold the tool, engage the nut or bit, and resist the torque reaction forces (Radwin et al., 1989; Lindqvist, 1993). Prolonged, excessive exposure to such vibration could cause hand-arm vibration syndrome (Griffin, 1990; Aiba et al., 1999). Because of the vibration interference, a higher grip force is often applied to such tools to maintain stability in performing tasks (Radwin et al., 1987). Whereas the impact torque could directly cause injuries (Friden and Lieber, 1995; Armstrong et al., 1995), the repetitive forceful actions combined with the vibration exposure could significantly increase the incidence of carpal tunnel syndrome and other injuries and disorders (Cannon et al., 1981; Silverstein et al., 1987). Therefore, it is useful to have a comprehensive understanding of the characteristics of the impact wrench vibration and torque exposures and to develop effective methods to monitor and control them.

The conventional method for the measurement and risk assessment of hand-transmitted vibration exposure has been

* Corresponding author. Engineering & Control Technology Branch, HELD, National Institute for Occupational Safety and Health, CDC, 1095 Willowdale Road, MS L-2027, Morgantown, WV 26505, USA. Tel.: +1 304 285 5840; fax: +1 304 285 6265.
E-mail address: xxu1@cdc.gov (X.S. Xu).

0169-8141/$ – see front matter Published by Elsevier B.V.
doi:10.1016/j.ergon.2008.05.006

standardized (ISO 5349-1, 2001 and ISO 5349-2, 2001). This method requires measuring the vibration on a tool in the hand contact or grip areas using tri-axial accelerometers. Whereas the acceleration spectra or vibration values measured with the conventional method in the dominant vibration axis on the impact wrenches or nut runners have been reported (e.g., Griffin, 1997; Bovenzi et al., 1997; Aiba et al., 1999), little information on the vibration in the other axes or the total vibration spectra can be found in the literature. The reported tool acceleration spectra may reasonably represent the vibration hazard at the hand–tool interface, but they could be significantly different from that actually transmitted to each anatomical structure of the hand-arm system. Because the transmitted vibration is likely to be more closely associated with the vibration-induced health effects, it is important to characterize and understand the transmitted vibration. Whereas the vibration transmissibility in the hand-arm system excited from a single-axis vibration exciter has been studied in controlled laboratory conditions by many researchers (e.g., Reynolds and Angevine, 1977; Pyykkö et al., 1976; Gurram et al., 1994; Sörensson and Lundström, 1992), the characteristics of multi-axis vibration transmissibility, especially those under real working conditions, have not been sufficiently investigated. Little information on the vibration transmitted to the hand-arm system during the operations of impact wrenches is available. Although the ISO frequency weighting for the risk assessment is established based on subjective sensation data that must be influenced by the transmitted vibration, the exact relationship between the ISO-weighted acceleration and the acceleration at a specific location of the hand-arm system has not been sufficiently investigated.

A convenient and reliable direct reading method for monitoring the exposure at workplaces is also desired to help achieve effective control of the vibration exposure. Because the accelerometers and their fixtures required in the standardized measurement method must occupy some space in or near the hand contact areas, they could interfere with the hand grip and wrench operation. Such interference may be tolerable if the measurement lasts for a short period of time, but continuous interference may annoy and unsafely impede the tool operator. Moreover, the vibration measured directly on the impact wrench could include a significant dc-shift (Griffin, 1990), as also observed in the current study. This requires careful examination of the measured data. Therefore, whereas the standardized method is designed to conduct the measurement for a limited time for risk assessment by an experienced investigator, an alternative method is required to continuously monitor the vibration exposure.

The measurement of vibration transmitted to the wrist may be an acceptable alternative approach for several reasons. First, the above-mentioned interference can be avoided by measuring the wrist vibration using a dosimeter equipped with a tri-axial accelerometer (Dong et al., 2001); the development of such a device has been shown to be technically feasible. Second, because the hand can serve as a mechanical filter that can effectively reduce high frequency vibration or shock, the requirements of the accelerometer for the wrist vibration measurement are much lower than those for the tool vibration measurement. At least, the dc-shift problem can be eliminated using the wrist method, and the reliability of the measurement can be significantly increased. Third, whereas reliable and practical methods have not been developed to measure the hand forces or to characterize hand and arm postures at workplaces, these important risk assessment factors can be at least partially taken into account if the wrist vibration acceleration is used as a measure for the risk assessment. Fourth, the fundamental resonance (16–50 Hz) of the hand-arm system can be well reflected in the wrist vibration transmissibility (Thomas and Beauchamp, 1998; Dong et al., 2005); as is also demonstrated in the current study. Therefore, it is reasonable to hypothesize that the accelerations measured at the wrist may provide an acceptable vibration measure for assessing the vibration-related disorders at least in the wrist and arm structures. Moreover, if the dynamic torque is reliably correlated with the vibration measured at the wrist, the wrist acceleration may also be used as an alternative approach to qualitatively estimate the severity of the dynamic torque exposure. However, although a few investigators have actually used the on-the-hand or on-the-wrist methods in some studies (e.g., Thomas and Beauchamp, 1998; Dong et al., 2003), they have not been sufficiently evaluated. Whereas further studies are required to confirm the above-mentioned useful features, their limitations or weaknesses should also be identified so that such methods can be appropriately used in field studies and applied in the development of an on-the-wrist vibration dosimeter.

Many epidemiological studies reported that the vibration exposure duration was an essential factor associated with hand-arm vibration syndrome (e.g., Griffin et al., 2003; Xu et al., 1989). The ISO-standardized method also requires quantifying both daily and life-time exposure durations for the risk assessment (ISO 5349-1, 2001). The durations have usually been estimated on the basis of the workers' claims of exposure duration, which may not be considered reliable. Several studies reported that workers tend to overestimate the exposure duration (e.g., Palmer et al., 2000; Akesson et al., 2001). The vibration measured at the wrist may be used to accurately quantify not only the total exposure duration of an individual but also the work–rest cycles that may also be important for understanding and assessing the vibration- and torque-induced injuries and disorders. However, the effectiveness of this duration measurement method has not been sufficiently evaluated.

To understand the transmitted vibrations during impact wrench operation and to help develop a practical and effective method to monitor, assess, and control the vibration and torque exposures, this study aimed to investigate the characteristics of the vibrations transmitted to the wrist and elbow and to evaluate the on-the-wrist and on-the-elbow methods. The relationships among tool handle vibration, wrist vibration, and elbow vibration were examined based on the vibrations measured in the operations of 15 impact wrenches on a simulated workstation. The effectiveness of the duration measurement based on wrist vibration measurement was evaluated. The correlation between wrist vibration and nut torque was also explored in this study.

2. Materials and methods

2.1. Simulated workstation and tools

The simulated impact wrench workstation shown in Fig. 1a, as proposed by an ISO ad hoc group for the revision of ISO 8662-7 (1997), was constructed and used in this study. The purpose of the task was to seat 10 nuts during each paced 30-s trial. The task would therefore theoretically even out the vibration exposure within each trial while simulating actual workday vibration emissions. Briefly, the workstation was set up with two removable 38 mm thick hardened steel plates vertically mounted on a concrete block. Channels were machined on the reverse side of the plates to constrain the 10 M20 $\times$ 60 mm grade eight steel bolts through holes in two evenly-spaced rows of five bolts each. Each bolt was fitted with a nut and two Belleville washers stacked in parallel along with a matching flat washer. Two complete sets of new bolts, washers, and nuts were used during the tests.

Five models of impact wrenches, with three samples of each model for a total of 15 tools were used in the test (see Fig. 1b): (A1–3) Ingersoll-Rand Model 2135Ti (max torque: 848 Nm, weight: 3.95 lb); (B1–3) Atlas Copco Model EP12PTS150-HR13-AT (max torque: 150 Nm, weight: 5.5 lb); (C1–3) Chicago Pneumatic Model CP749 (max torque: 612 Nm, weight: 5.25 lb); (D1–3) Chicago

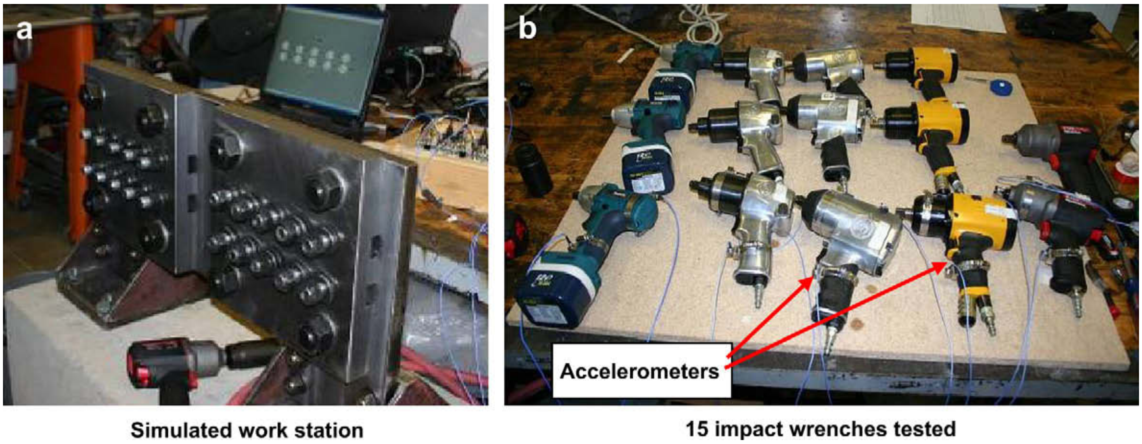

Fig. 1. Simulated workstation and impact wrenches tested.

Pneumatic Model CP7733 (max torque: 746 Nm, weight: 5.6 lb); and (E1–3) Makita Model BTW120 (max torque: 120 Nm, weight: 3.5 lb). The first four listed tool models are pneumatic tools which were supplied with shop air at 689 kPa (100 psi). The Makita model is a battery-powered tool. The 12 V battery packs for each of the three Makita tools were fully charged at the beginning of each test session. All of the tools were set to their maximum available torque settings. Prior to this study, these 15 tools were used in 4 other similar laboratory studies; all tools were in good working condition.

2.2. Subjects, instrumentation, and test procedures

To measure the transmitted vibration, two in-house packaged tri-axial accelerometers (Kionix, Model KXM52-1050) were placed on the wrist and elbow of the subject's dominant arm using double-sided tape, self-adherent wrap, and medical tape, as shown in Fig. 2. Medical tape was also used to hold the wires of the accelerometer in place along the arm, shoulder, and back (see Fig. 2b). The signals of the accelerations were input to a data acquisition card (National Instrument, DAQCard-6036E) and a LabVIEW™ program was developed to analyze and record the spectra in the one-third octave bands from 6.3 to 400 Hz.

For the purpose of this study, the vibration on the tool handle of each tool was measured using a tri-axial accelerometer (PCB, Model 356B11). Significant dc-shift was observed in the preliminary tests when no mechanical filter was applied. To resolve this problem, thin layers of rubber (3 mm) were placed underneath the mounting block of each accelerometer as needed, which was validated from our previous studies (Dong et al., 2003, 2004). The signals from these accelerometers were input to a data acquisition system (B&K Model 3032A) to collect and analyze the tool vibration data. The results were directly expressed in the one-third octave bands at center frequencies ranging from 6.3 to 400 Hz. The measurements of vibration on the tool and arm were synchronized.

Six experienced male operators of impact wrenches were recruited to perform the tests. The study protocol was reviewed and approved by the NIOSH Human Subjects Review Board. Upon arrival, the subject was first explained the test procedure, signed the consent form, and was trained to perform the simulated work task. To protect the subject from cuts from the accelerometer assembly fixed on the handle in the grip zone, each subject was required to wear a pair of non-anti-vibration gloves (Mechanix Wear, Original), which is also shown in Fig. 2b. Each subject completed 5 trials with each of the 15 tools for a total of 75 trials in a test session. The testing order of the 15 tools was independently randomized for each subject. For each trial, the subject needed to seat 10 nuts onto plate-mounted bolts in a 30-s period while vibration was measured both on the tools and from the subject's forearm. A custom graphical display was developed in-house based on LabVIEW™ software to control the pace of the task, guiding the subject to seat each nut in approximately 2 s and then move to the next nut in 1 s. The display consisted of 10 dial gauges representing the 10 nuts to be tightened, each followed by a message to move to

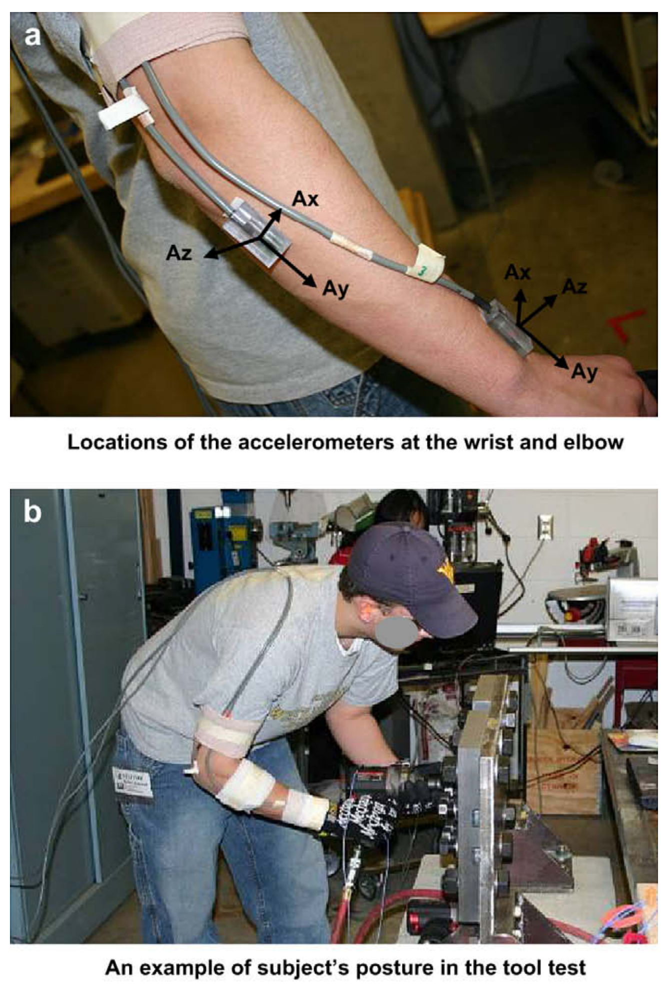

Fig. 2. Vibration measured at subject's wrist and elbow by tri-axial accelerometers.

the next nut. The subjects were very consistent with their pace throughout the trials, completing each trial within 30 ± 1.5 s.

In an effort to simulate the actual work situations in the field, postures were not controlled, and the subject could use a posture judged to be most comfortable. The six subjects generally adopted one of three postures wherein the tool handle was oriented vertically, horizontally, or at a 45° angle. An example of the 45° working posture is shown in Fig. 2b.

With the measured spectrum in each vibration direction, the root-sum-of-squares (rss) of the tri-axial accelerations (ISO 5349-1, 2001) were calculated from:

$$\begin{aligned} &\text{ISO-weighted tool rss acceleration}: A_{\mathrm{WT}} = \sqrt{\textstyle\sum_{i=1}^{19}\left[(w_iA_{Txi})^2+(w_iA_{Tyi})^2+(w_iA_{Tzi})^2\right]} \\ &\text{Wrist rss acceleration}: A_{\mathrm{Wrist}} = \sqrt{\textstyle\sum_{i=1}^{19}\left[A_{Wxi}^2+A_{Wyi}^2+A_{Wzi}^2\right]} \\ &\text{Elbow rss acceleration}: A_{\mathrm{Elbow}} = \sqrt{\textstyle\sum_{i=1}^{19}\left[A_{Exi}^2+A_{Eyi}^2+A_{Ezi}^2\right]} \end{aligned} \quad (1)$$

where A_{Tx}, A_{Ty}, and A_{Tz} are root-mean-square (rms) values of the accelerations measured on the tool handle, A_{Wx}, A_{Wy}, and A_{Wz} are measured at the wrist, and A_{Ex}, A_{Ey}, and A_{Ez} are measured at the elbow. For the purpose of this study, the integration for the rss values was performed from 6.3 Hz ($i=1$) to 400 Hz ($i=19$).

2.3. Measurement of vibration transmissibility

After finishing the tool test, an additional vibration transmissibility test on a 1-D vibration test system (Unholtz-Dickie, TA250-S032-PB) was performed. The vibration from the shaker was input to the subjects' hand through an instrumented handle equipped with an accelerometer (PCB, Model 356A12) and a pair of force sensors (Kistler, 9212). As shown in Fig. 3, each subject was instructed to keep the same posture and apply the same grip and push forces as he perceived in the tool test on an instrumented handle fixed on the shaker of the test system. The height from the floor to the upper row of nuts was matched with the height from an elevated platform and force plate (Kistler, 9286AA) to the instrumented handle of the shaker. The handle was angled to match each subject's work posture. A broad-band random vibration with a power spectral density equal to 3.0 $(\mathrm{m/s^2})^2$/Hz and frequency range from 6.3 to 1250 Hz was used as the excitation in the measurement. The applied grip and push forces were recorded, but these force values were withheld from the subject. Whereas the instrumented handle provided the measurement of the input vibration, the accelerometers fixed on the subject's wrist and elbow were used to measure the transmitted vibrations. For each subject, six trials were performed, and each trial lasted 30 s.

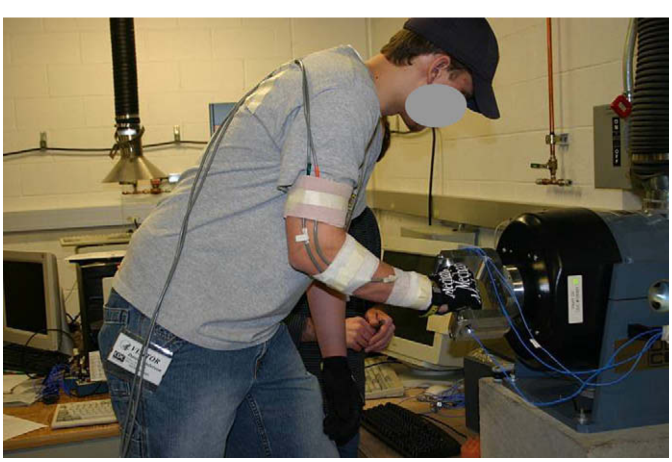

Fig. 3. During the transmissibility test, the subject is instructed to keep the same posture and apply the same grip and push forces as he perceived in the tool test.

The transmissibility at each center frequency in the one-third octave bands from 6.3 to 400 Hz was evaluated using the root-sum-of-squares of the tri-axial accelerations, which is expressed as follows:

$$T_{r\_k}(\omega) = \frac{\sqrt{A_{x\_k}^2(\omega)+A_{y\_k}^2(\omega)+A_{z\_k}^2(\omega)}}{\sqrt{A_{hx}^2(\omega)+A_{hy}^2(\omega)+A_{hz}^2(\omega)}}; \quad k = \text{Wrist, Elbow} \quad (2)$$

where A_{x_k}, A_{y_k}, and A_{z_k} are root-mean-square (rms) values of the accelerations measured either at the wrist or elbow in the x, y and z axis, respectively; and A_{hx}, A_{hy}, and A_{hz} are the accelerations measured on the instrumented handle.

2.4. Measurement of impact wrench torque

To explore the correlation between the wrist vibration and the torque applied on the nut, the torque of the tools was measured indirectly using a click-type torque wrench. One subject performed four trials for each tool to obtain the averaged torque of the tool. Within each trial, the amount of torque required to unseat each of the 10 nuts was measured and averaged. Torque of the three battery-powered tools was below that of the operating range of the torque wrench used in this study, therefore only the 12 pneumatic tools were included in the torque study. The testing order of the 12 tools was randomized. Mean and standard deviation of each of the

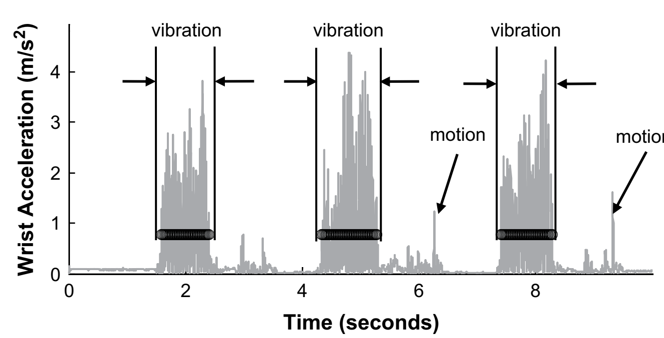

Fig. 4. An example result for the detection of vibration exposure duration from the tri-axial wrist accelerometer.

12 tools across 4 trials (4×10 nuts) were calculated. Differences among individual tools were also investigated.

2.5. Calculation of vibration exposure duration

Vibrations measured at the wrist were used to develop an approach to quantify the vibration exposure duration. As shown in Fig. 4, a threshold level was established so that the amplitudes of the tri-axial acceleration data exceeding this level indicate vibration exposure. The mean (μ) and standard deviation (σ) of the raw data in the full recorded range were used to determine the threshold ($=\mu + \sigma$). The wrist accelerometers had a dc to 1500 Hz bandwidth and were sensitive to low frequency motion such as when moving the tool from one nut to the next. An algorithm was developed to first find the starting point of the major segments above the vibration threshold, and then eliminate the segments that are too close to another vibration segment. This helps to avoid detecting signals resulting from low frequency hand-arm movements as vibration, as indicated in Fig. 4. The same algorithm was also applied to the tool vibration time history data simultaneously recorded on the B&K data acquisition system. Agreement between these two duration measurements was evaluated using correlation analysis. In the statistical analysis, subjects and tools are factors being considered, and the interactions of these factors were investigated.

2.6. Statistical analyses

Where appropriate, univariate General Linear Model analysis of variance (ANOVA) tests were performed to identify significant study factors. Wherever necessary, Tukey's Honestly Significant Difference (HSD) post hoc pair-wise comparisons were performed.

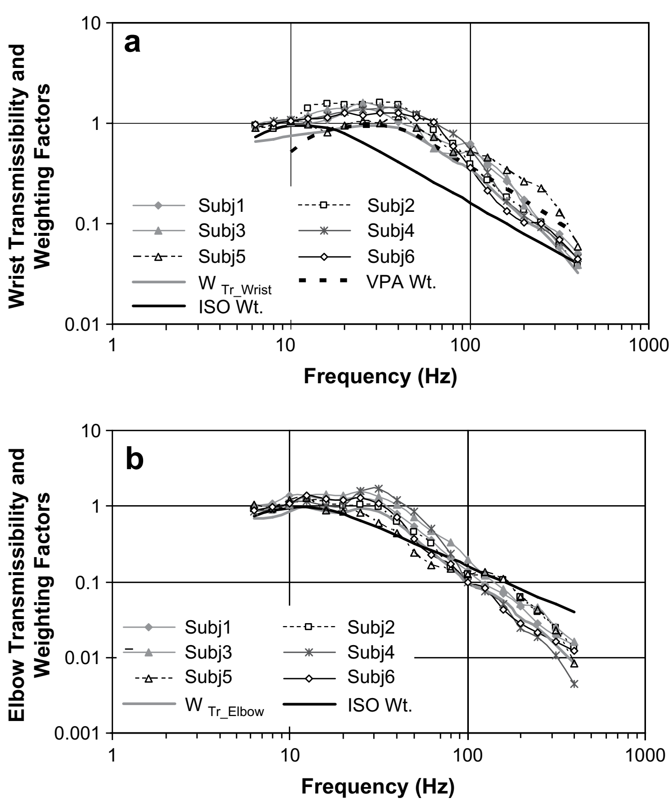

Fig. 5. Vibration transmissibility from the instrumented handle to the subject's (a) wrist and (b) elbow.

All ANOVAs and Tukey's HSD tests were performed using SPSS statistical software (SPSS Inc., version 14.0). These analysis results were considered significant at the $p < 0.05$ level.

3. Results

3.1. Vibration transmitted to wrist and elbow

The vibration transmissibility functions measured in the six trials of the transmissibility test on the shaker for each subject were averaged, and the averaged transmissibility functions for the six subjects are plotted in Fig. 5. The intra-subject variation, expressed in terms of average coefficient of variation of the wrist transmissibility, was observed to be reasonable for the six subjects (0.10–0.16, with one subject at 0.32). The inter-subject difference measured with the average coefficient of variation of wrist transmissibility across six subjects is also reasonable (0.20). The transmissibility measured at the wrist at frequencies above 10 Hz is generally greater than that measured at the elbow. At both locations, the transmissibility values at frequencies less than 50 Hz are generally more than 10 times those beyond 315 Hz.

The transmissibility-based weighting (W_{Tr}) was derived from the average transmissibility of the six subjects. For a direct comparison with ISO frequency weighting, W_{Tr} is normalized to the maximum ISO weighting factor ($=0.958$) at the maximum transmissibility, which is expressed as follows:

$$\begin{aligned} W_{Tr\_Wrist} &= 0.958 T_{r\_Wrist}(\omega)/T_{r\_Wrist\_Max} \\ W_{Tr\_Elbow} &= 0.958 T_{r\_Elbow}(\omega)/T_{r\_Elbow\_Max} \end{aligned} \quad (3)$$

The transmissibility-based weighting (W_{Tr}) and the ISO weighting are also presented in Fig. 5. As can be seen in the figure, they follow a similar trend, but they are significantly different in a large part of the hand-arm resonant frequency range (16–50 Hz). Whereas the maximum ISO weighting is at 12.5 Hz, the peak value of the transmissibility-based weighting is in the middle (31.5 Hz) of the fundamental resonance range of the hand-arm system. The elbow transmissibility-based weighting seems closer to the ISO weighting than the wrist transmissibility-based weighting at frequencies less than 100 Hz.

A few researchers have recently reported the frequency weighting derived from the vibration power absorption (VPA) in the palm, hand-back, wrist and forearm (Dong et al., 2006; Dong et al., 2008). For a direct comparison, the palm VPA-based weighting (VPA Wt) is also plotted in Fig. 5a. The transmissibility-based weighting at the wrist is very similar to the VPA-based frequency weighting at frequencies greater than 16 Hz, which suggests that wrist transmissibility is closely associated with the vibration power absorption in the wrist and the tissues in the vicinity of the wrist.

Fig. 6 illustrates the comparisons among the ISO-weighted tool acceleration spectra and the acceleration spectra measured at the wrist and elbow. Whereas their basic shapes in the frequency domain are similar, their specific values at each frequency are generally different from each other, especially at frequencies higher than 20 Hz. The predominant components of the vibration measured at the wrist are generally between 20 and 200 Hz. Consistent with that observed in Fig. 5a, the wrist vibration at higher than 315 Hz is generally very small. Also consistent with that shown in Fig. 5, the acceleration measured at the elbow is generally lower than that measured at the wrist. The ISO-weighted tool acceleration is generally between the wrist and elbow accelerations from 63 to 200 Hz, but it is generally greater than both at frequencies above 315 Hz.

Table 1 lists the ANOVA results of the rss magnitudes calculated from Eq. (1) for the three vibration measures. The results indicate that both subject and tool are significant factors for all three types

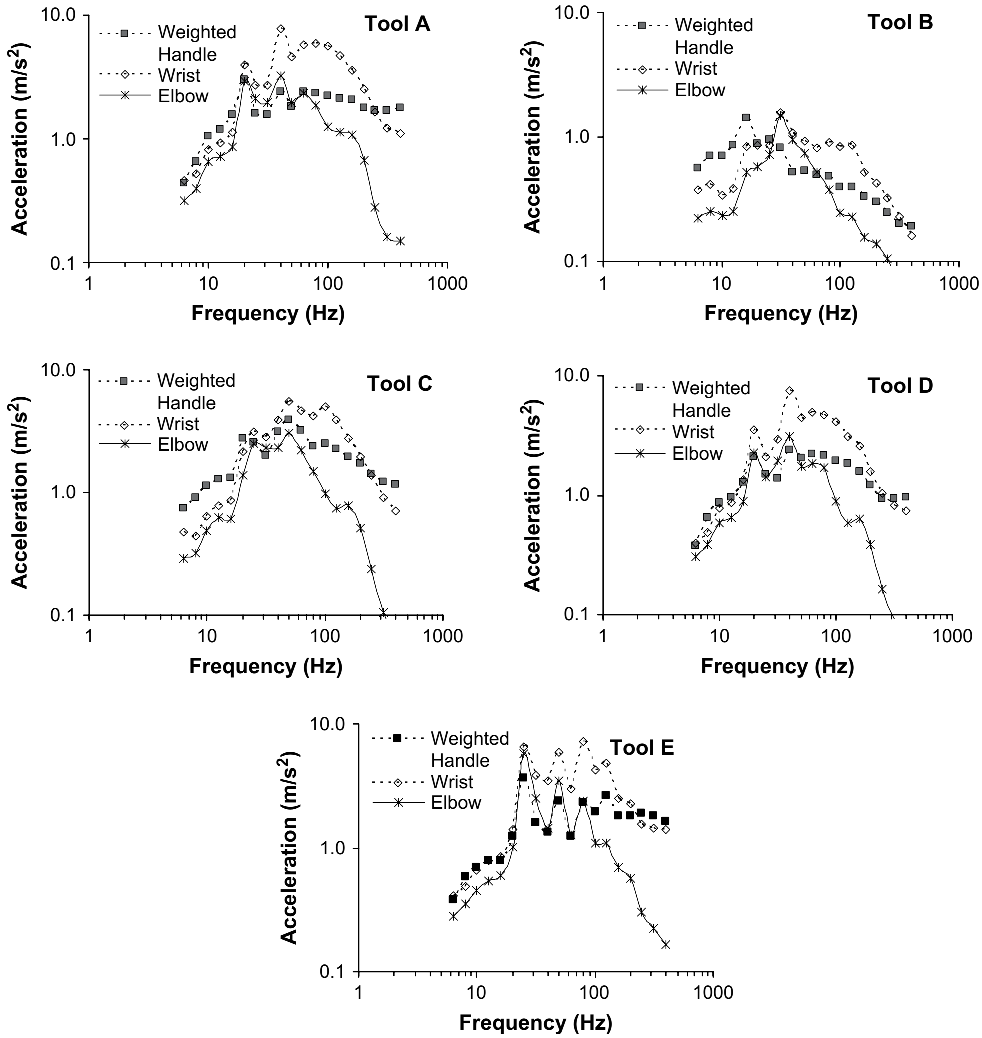

Fig. 6. ISO-weighted accelerations measured on the handle of the five types of tools and unweighted accelerations from the operator's wrist and elbow.

of vibration measures. The interaction between subject and tool for each vibration measure is also statistically significant, which suggests that the vibrations measured in the operation of the same tool by different subjects could vary in a certain range.

Table 2 contains the three different vibration measures by subject. Consistent with the observation made from the results shown in Fig. 6, the wrist acceleration is the highest (7.49 m/s^2), the elbow acceleration is the lowest (4.05 m/s^2), and the ISO-weighted tool acceleration is in the middle (6.26 m/s^2). The post hoc analysis suggests that these differences are significant ($p < 0.001$). The ranking of the standard deviations of these three measures also follows the same sequence. As a result, their coefficients of variance are not statistically different ($p \geq 0.15$).

Table 2 also contains the ranking of the subject vibration exposure severity. They can be classified into four groups in terms of their relative differences. All three types of measures consistently suggest that Subject T is in the highest vibration group ($p < 0.001$) and Subject W in the lowest one ($p < 0.001$). Although the exposure levels for the remaining subjects are not always significantly different from each other, the group orders are also the same except that subjects M and Q switch their group positions in the ISO-weighted acceleration measure.

Table 3 contains the mean rss values of three vibration measures for each tool model. Among the ISO-weighted tool accelerations, the tool models can be classified into four groups: whereas Tool B has the lowest vibration emission, Tool C is the highest one; the vibration emissions of Tools D and E are not significantly different, but they are lower than that of Tool A. However, when classified via wrist and elbow accelerations, the tools can only be separated into three groups. Tool B is still the lowest for these two vibration measures. The ranking of the tools judged from the elbow acceleration and ISO-weighted tool acceleration are the same, but Tools

Table 1
ANOVA results of the ISO-weighted accelerations measured on the 15 tool handles and simultaneously recorded accelerations at the wrists and elbows of the 6 subjects.

Dependent variable	Source of variance	Sum of squares	Degrees of freedom	Mean square	*F*	*p*<
Weighted tool vibration	Tool	1657.7	14	118.4	413.7	0.001
	Subject	150.4	5	30.1	105.1	0.001
	Tool × Subject	206.3	70	2.9	10.3	0.001
	Error	103	360	0.3		
Wrist vibration	Tool	2183.1	14	155.9	149.6	0.001
	Subject	870.1	5	174	166.9	0.001
	Tool × Subject	503	70	7.2	6.9	0.001
	Error	375.3	360	1		
Elbow vibration	Tool	433.2	14	30.9	56.7	0.001
	Subject	519.4	5	103.9	190.5	0.001
	Tool × Subject	249.3	70	3.6	6.5	0.001
	Error	196.3	360	0.5		

Table 2
Tukey's HSD post hoc pair-wise comparison results for ISO-weighted tool handle, wrist and elbow rss acceleration means for the six study participants ($n = 75$).

	Statistics across six subjects			Mean rss acceleration by subject					
Weighted tool vibration (m/s^2)				Low → high					
	Mean	SD	CV	W	M	Q	S	D	T
	6.26	2.08	0.33	5.64	5.64	6.18	6.12	6.67	7.29
Wrist vibration (m/s^2)	Mean	SD	CV	W	Q	M	S	D	T
	7.49	2.54	0.33	5.55	6.68	7.43	7.49	7.66	10.16
Elbow vibration (m/s^2)	Mean	SD	CV	W	Q	S	M	D	T
	4.05	1.32	0.32	2.60	3.46	3.93	4.08	4.09	6.16

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

Table 3
Tukey's HSD post hoc pair-wise comparison results for ISO-weighted tool handle, wrist and elbow rss acceleration means for the five tool models ($n = 90$).

	Statistics across five tool models			Mean rss acceleration by tool model				
Weighted tool vibration (m/s^2)				Low → high				
	Mean	SD	CV	B	D	E	A	C
	6.26	2.17	0.35	2.86	6.26	6.56	6.99	8.61
Wrist vibration (m/s^2)	Mean	SD	CV	B	D	C	A	E
	7.49	2.96	0.39	3.20	7.96	8.31	8.90	9.10
Elbow vibration (m/s^2)	Mean	SD	CV	B	D	E	A	C
	4.05	1.76	0.44	2.19	4.17	4.46	4.54	4.89

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

C and E are positioned at different rankings when wrist acceleration is used for the judgment. Furthermore, Tool A is significantly different from other tools according to ISO-weighted tool acceleration, but this is not the case for either wrist or elbow accelerations.

Fig. 7 shows the results of Pearson's correlation analyses among the three vibration measures. Each analysis used all 450 pairs of values (6 subjects × 15 tools × 5 trials). Although the magnitudes of the three vibration measures are significantly different, they are reliably correlated with each other ($p < 0.001$). Similar analyses were performed on the data of the three measures for each subject. Although the specific relationships vary with subjects, their correlations are also statistically reliable (R^2-value in the range of 0.49–0.77, $p < 0.001$).

3.2. Tool torque and its relation to vibration

The torque required to loosen the nuts tightened with the battery-powered impact wrench was too low to be reliably measured using the torque wrench used in this study. This also indicates that the torque values of these wrenches are not comparable with those of the pneumatic tools. Whereas there were no data available for exploring the relationship between the vibration and torque of the battery-powered wrenches, the correlation analysis between the wrist vibrations and the torques of the 12 pneumatic tools was performed. The boxplot in Fig. 8 shows the summary result of the torque for each of the 12 tools. Although there are obvious inter-nut and inter-trial variances, the results show consistency among the three tools in each of the four tool models. The torques among the four tool models are reliably different ($p < 0.001$). As shown in Fig. 9, the tool torque is correlated with the acceleration measured at the wrist and that measured at the elbow.

3.3. Vibration exposure duration

The exposure durations for each subject in each trial from the vibration data measured at wrist are determined using the same algorithm, with the selected threshold (e.g., 0.8 m/s^2) shown in Fig. 4. The ANOVA results presented in Table 4 indicate that both subject and tool are significant factors, and the interaction between them is also significant. The boxplot in Fig. 10 shows the summary result of vibration exposure duration by subjects and tools.

Several pairs of randomly selected time history data of the wrist and tool accelerations were visually compared. The comparison found that the acceleration directly measured on the tools had a lower noise level than that measured at the wrist. Therefore, the exposure duration was also determined from the tool vibration data to assess the reliability of the duration determined from the wrist vibration. Fig. 11 clearly indicates that the durations determined from these two vibration measures are highly correlated. The average difference between these two duration measures is only 2.3%.

4. Discussion

This study examined the characteristics of the wrist and elbow vibrations transmitted from the handles of 15 impact wrenches and their association with the ISO-weighted acceleration measured on the tools. The relationship between the wrist acceleration and the wrench torque was also explored in this study. The results can be used to help improve the risk assessment method and to assist the development of a convenient method for continuously monitoring vibration exposure.

4.1. Vibrations transmitted to wrist and elbow

The results of this study indicate that the root-sum-of-square values of the tri-axial accelerations measured at the wrist and at the elbow are each correlated with the ISO-weighted tool acceleration (Fig. 7). This suggests that the ISO frequency weighting at least partially reflects the nature or characteristics of wrist and elbow vibration exposures. This may further partially explain why wrist disorders could be correlated with the ISO-weighted acceleration, as reported by Malchaire et al. (2001).

However, the results of this study also suggest that there is some room for the improvement of the ISO frequency weighting. The total vibration transmissibility illustrated in Fig. 5 shows a resonant peak at 31.5 Hz. Similar phenomena have been reported by several other researchers (Thomas and Beauchamp, 1998; Gurram et al., 1994; Pyykkö et al., 1976). As also shown in Fig. 5, the frequency weighting (VPA Wt) derived from the vibration power absorbed in the wrist and surrounding structures has similar frequency

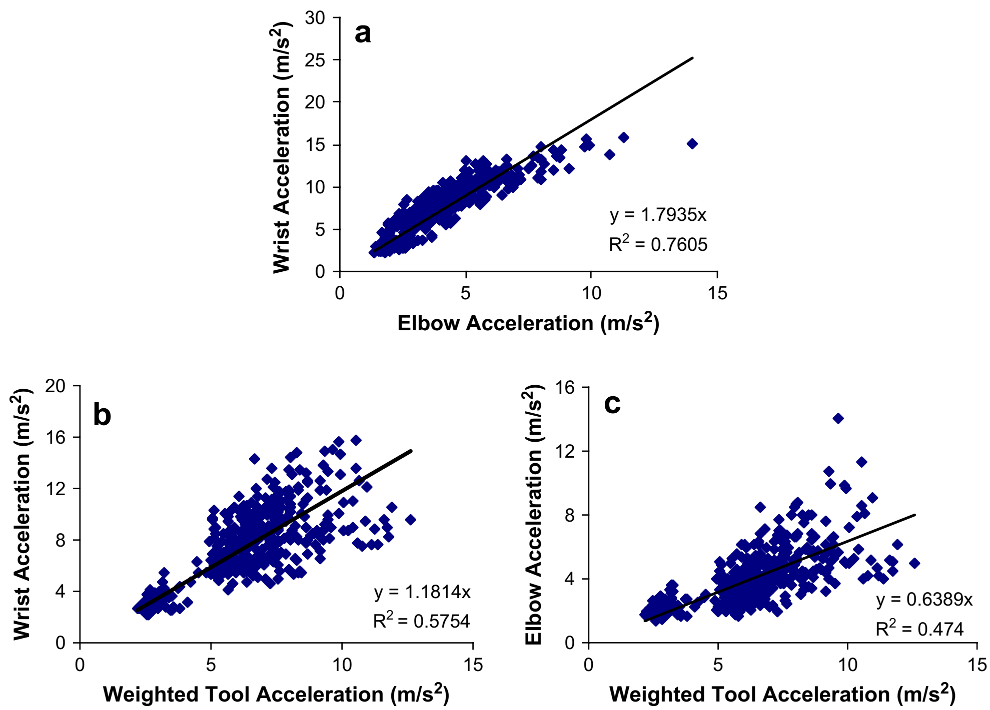

Fig. 7. Relationships among vibrations measured on the tool handle and from the subject's hand-arm system.

dependency in the resonant frequency range (Dong et al., 2006; Dong et al., 2008). However, this important resonance is not sufficiently reflected in the ISO weighting. The wrist and elbow transmissibility-based frequency weightings may be used to help improve the ISO frequency weighting, at least for assessing wrist and elbow vibration exposure risks. To test this hypothesis at workplaces, a wrist vibration dosimeter can be developed to quantify the exposure.

The results of this study indicate that the transmitted vibrations generally depend on the tool vibration (Table 1). However, many other factors could also affect the vibrations measured at the wrist and elbow. The tool vibration is measured at one point on the handle in the hand grip area (Fig. 1), which may not be fully representative of the vibration actually transmitted to the hand.

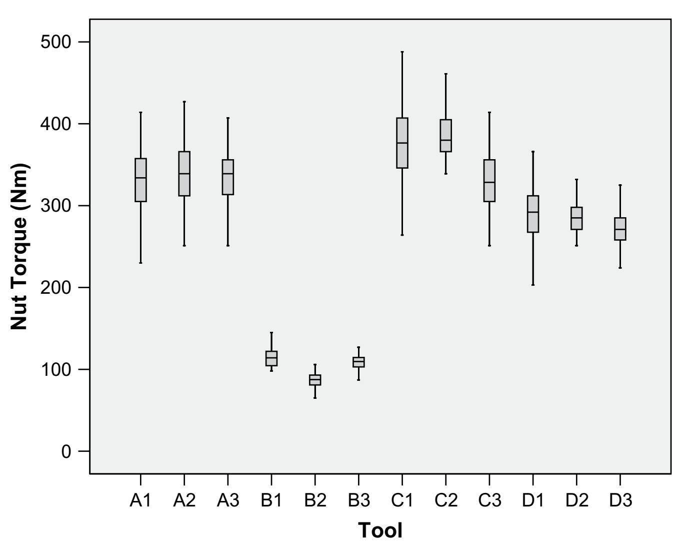

Fig. 8. Distributions of the torque for each of the 12 pneumatic impact wrenches from four 10-nut trials ($n = 40$). The boxes represent the inner quartile range; the whiskers extend to the 5th and 95th percentiles.

The transmitted vibration is also usually affected by individual mechanical impedance that is further affected by the applied hand forces and postures of the hand and arm (Dong et al., 2005). These factors could also affect the tool vibration itself (Dong et al., 2004). These observations explain why the subject and the interaction of subject and tool are significant factors of the vibrations measured at

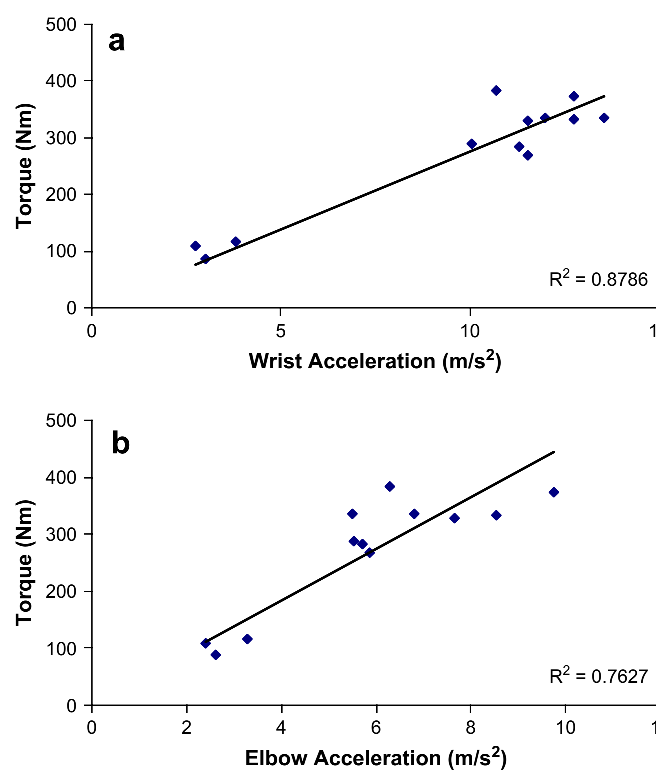

Fig. 9. Relationship between the tool torque and vibration measured at the operator's (a) wrist and (b) elbow.

Table 4
ANOVA table for vibration exposure duration of the five tool models and from the six subjects.

Dependent variable	Source of variance	Sum of squares	Degrees of freedom	Mean square	F	$p<$
Wrist	Tool	12.1	14	0.9	8.7	0.001
Vibration	Subject	129.5	5	25.9	261.4	0.001
Duration	Tool × Subject	119.6	70	1.7	17.2	0.001
	Error	35.7	360	0.1		

the wrist and elbow (Tables 1 and 2), and the rankings of the exposure severity judged from the three vibration measures may not be exactly the same, as presented in Tables 2 and 3.

The ISO-standardized method requires consideration of the hand forces and postures in the risk assessment (ISO 5349-1, 2001). So far, however, no method has been specified on how to include them in the calculation of the exposure dosage. Further, no convenient and reliable method for their measurements at workplaces has been developed. On the other hand, as above-mentioned, the vibrations measured at the wrist and elbow can at least partially reflect the influences of these factors. Therefore, the wrist and elbow accelerations may be used as alternative vibration measures for the risk assessment of the disorders in the wrist, forearm, and elbow at workplaces. Practically, it is easier to measure wrist vibration than elbow vibration because an elbow vibration meter may significantly interfere with the movement of the arms during work activities. Since elbow vibration and wrist

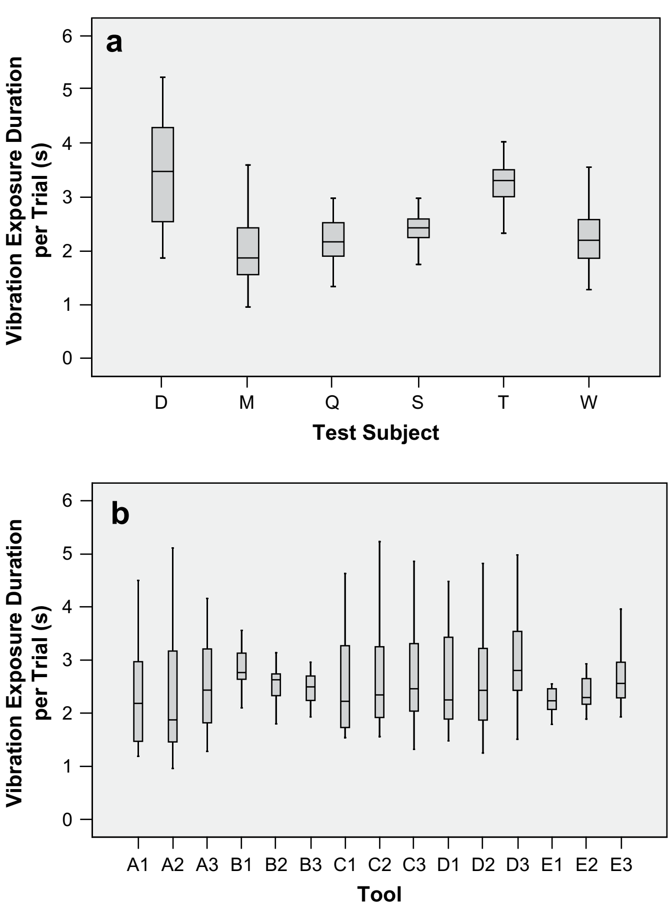

Fig. 10. Vibration exposure duration measured on the wrist for (a) each test subject while operating all 15 tools ($n = 75$) and (b) each tool by all six subjects ($n = 30$). The boxes represent the inner quartile range; the line inside each box is the median value; the whiskers extend to the 5th and 95th percentiles.

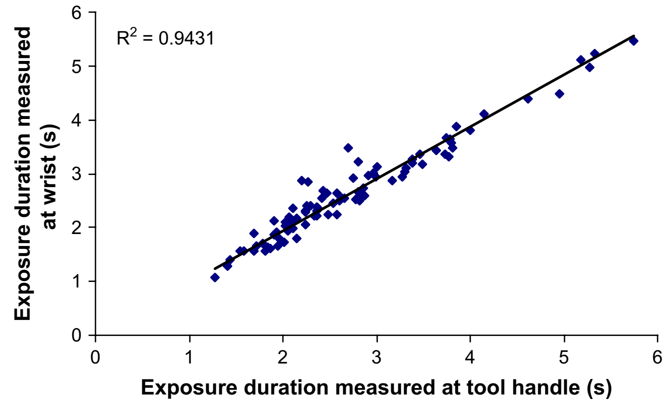

Fig. 11. Correlation between vibration exposure duration measurement from the tool handle and from the operator's wrist.

vibration are highly correlated (Fig. 7), it is also unnecessary to measure both of them.

The current ISO 8662-7 (1997) specifies a test method for screening impact wrenches. Because the loading device recommended in the standard may not provide a reliable and realistic torque load during the test, the Standard Working Group has proposed its replacement, which is similar to the simulated workstation used in the current study (Fig. 1). The coefficients of variance (CV) listed in Table 3 suggest that the ISO-weighted acceleration measurements on the tool handle are more sensitive than measurements at the wrist and elbow for ranking the tools. As also indicated in Table 3, however, if the differences in the vibration emissions of any two tools are sufficiently large, as in the case of Tool B and any other tool, their ranking order remains unchanged, regardless of the type of vibration measurement used for the judgment. Therefore, the wrist or elbow vibration may also be used as an alternative measure for screening impact wrenches at workplaces. These observations also suggest that the on-the-wrist or on-the-elbow method may also be used to help select better anti-vibration devices such as anti-vibration gloves and wraps when used with the impact wrenches.

Another application of the on-the-wrist or on-the-elbow method is for checking the validity of the tool vibration measurement if such a measurement is necessary. As-mentioned above, the dc-shift of the accelerometer is the most probable and critical problem in tool vibration measurement, but it will not interfere with wrist or elbow vibration measurements. Many portable vibration dosimeters do not provide the vibration spectrum required to assess the severity of the dc-shift problem. A quick method to evaluate the test data is to measure the vibrations on both the tool and at the wrist using the same accelerometer and dosimeter. According to the results of the current study, the tool vibration measurement should be questioned if the ISO-weighted acceleration measured on the tool is significantly greater than the acceleration measured at the wrist.

It should be noted that the sampling rate of the wrist and elbow vibration measurements used in this study is 1024 Hz, which limits the range of the frequency analysis (theoretically up to 500 Hz) and the application of the wrist vibration measurement. The standardized method (ISO 5349-1, 2001) requires the inclusion of the frequency components in the one-third octave bands up to 1250 Hz. As shown in Fig. 6, however, the wrist and elbow vibrations higher than 315 Hz are very small, and they would be unlikely to significantly affect the total vibration rss values in the wrench operation. As for long-term workday vibration monitoring in the field, trade offs must be made between data accuracy and device cost. To reduce the measurement error, the size of the wrist vibration meter should also be as small as possible and wrapped on the wrist as firmly as practical. The required memory or the physical size of the wrist vibration meter could become a critical issue if a higher sampling rate is required. The results suggest that the sampling rate (1024 Hz) used in this study is sufficient for the wrist vibration measurement for impact wrenches. Because the dominant vibration frequencies of the majority of tools are at or below 250 Hz (Griffin, 1990), it is anticipated that this sampling rate is sufficient for many tool applications when the wrist vibration method is used. However, because vibration at frequencies higher than 500 Hz is mostly concentrated in the fingers and palm tissues close to the contact surfaces (Wu et al., 2006), it may not be appropriate to use the on-the-wrist method to quantify the finger and contact tissue vibration exposures for their risk assessments.

4.2. Torque and vibration

It is useful to control tool torque to reduce wrist injury potential, but it is difficult to measure or monitor it during tool operation. The indirect method proposed in this study provides a practical solution for its measurement, which should be generally applicable at workplaces. The data obtained in the current study also suggest that there may be a relationship between the vibration and the tool torque (Fig. 9). However, the data may not be sufficient because there is lack of data in the range of 30–40 N m, which requires further studies. Furthermore, the relationship shown in Fig. 9 may not be applicable for electric tools.

4.3. Vibration exposure duration

The current study demonstrated that exposure duration can be accurately determined by measuring the wrist vibration. Results in Table 4 and Fig. 10 also show that the duration depends more on subjects than on tool types, even though both of them are significant factors. This suggests that personal habits may also play an important role in the vibration exposure. For example, in the case of the impact wrenches, individuals may trigger the tool differently, over or under-tightening the nuts. The accurate measurement of the work–rest cycle may also help elucidate the effects of the individual differences on the development of the vibration-induced disorders.

It should be noted that the specific threshold ($\mu + \sigma$) used in this study for determining the exposure duration was chosen based on the observation of the recorded time history data of the impact wrench vibration exposure. This threshold may not be generally applicable for some other types of tools. A different threshold may be required for each specific type of tool.

5. Conclusions

Based on the tri-axial accelerations measured at three locations (tool handle/instrumented handle, wrist, and elbow) during impact wrench operations and the transmissibility test, the current study characterized vibrations transmitted from the vibration sources to the operators' forearm. The current study confirmed that the severity of the vibration exposure during impact wrench operation depends on both tool and individual differences. Wrist and elbow vibration measurements can take into account both factors that may be further influenced by individual differences in biodynamic responses, hand forces, and hand and arm postures. This study found that the vibrations transmitted to the wrist and elbow are each reliably correlated with ISO frequency-weighted tool acceleration. The fundamental resonance of the hand-arm system in the range of 16–50 Hz is well reflected in the vibration measured at the wrist. This study also demonstrated that vibration exposure duration can be detected accurately and reliably using the on-the-wrist method. Although further study is required to confirm it, the current study reveals that wrist vibration is suggestively correlated with the torque produced by pneumatic impact wrenches. Therefore, with its advantages of posing the least interference with working tasks and avoiding the dc-shift problem, the on-the-wrist vibration measurement method may be used as a practical and effective alternative approach to quantify the impact wrench vibration exposure, and to continuously monitor and control the exposure at workplaces. It is also anticipated that such a method may also be applicable to other tools with dominant vibration frequencies similar to those of the impact wrenches.

6. Disclaimers

The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety & Health. The mention of trade names, commercial products, or organizations does not imply endorsement by the US Government.

References

Aiba, Y., Ohshiba, S., Ishizuka, H., Sakamotok, K., Moriokai, I., Miyashita, K., Iwata, H., 1999. A study on the effects of countermeasures for vibrating tool workers using an impact wrench. Industrial Health 37 (4), 426–431.

Akesson, I., Balogh, I., Skerfving, S., 2001. Self-reported and measured time of vibration exposure at ultrasonic scaling in dental hygienists. Applied Ergonomics 32 (1), 47–51.

Armstrong, R.B., Warren, G.L., Lowe, D.A., 1995. Mechanisms in the initiation of contraction-induced skeletal muscle injury. In: Gordon, S.L., Blair, S.J., Fin, L.J. (Eds.), Repetitive Motion Disorders of the Upper Extremity. American Academy of Orthopaedic Surgeons, Rosemont, IL, pp. 339–350.

Bovenzi, M., Apostoli, P., Alessandro, G., Vanoni, O., 1997. Changes over a workshift in aesthesiometric and vibrotactile perception thresholds of worker exposed to intermittent hand transmitted vibration from impact wrenches. Occupational and Environmental Medicine 54, 577–587.

Cannon, L.J., Bernacki, E.J., Walter, S.D., 1981. Personal and occupational factors associated with carpal tunnel syndrome. Journal of Occupational Medicine 23, 255–258.

Dong, R.G., Bader, J., Welcome, D., Rakheja, S., Schopper, A.W., 2001. An accurate method for measuring the exposure duration of hand-transmitted vibration. In: Proceedings of the 36th UK conference on human response to vibration, pp. 416–424.

Dong, R.G., McDowell, T.W., Welcome, D.E., Smutz, W.P., Schopper, A.W., Warren, C., Wu, J.Z., Rakheja, S., 2003. On-the-hand measurement methods for assign effectiveness of anti-vibration gloves. International Journal of Industrial Ergonomics 32, 283–298.

Dong, R.G., McDowell, T.W., Welcome, D.E., Warren, C., Schopper, A.W., 2004. An evaluation of the standardized chipping hammer test specified in ISO 8662-2. The Annals of Occupational Hygiene 48 (1), 39–49.

Dong, R.G., Welcome, D.E., Wu, J.Z., 2005. Frequency weightings based on biodynamics of fingers-hand-arm system. Industrial Health 43, 485–494.

Dong, R.G., Welcome, D.E., McDowell, T.W., Wu, J.Z., Schopper, A.W., 2006. Frequency weighting derived from power absorption of fingers-hand-arm system under z_h-axis. Journal of Biomechanics 39, 2311–2324.

Dong, J.H., Dong, R.G., Rakheja, S., Welcome, D.E., McDowell, T.W., Wu, J.Z., 2008. A method for analyzing absorbed power distribution in the hand and arm substructures when operating vibrating tools. Journal of Sound and Vibration 311, 1286–1309.

Friden, J., Lieber, R., 1995. Biomechanical injury to skeletal muscle from repetitive loading: eccentric contractions and vibration. In: Gordon, S.L., Blair, S.J., Fin, L.J. (Eds.), Repetitive Motion Disorders of the Upper Extremity. American Academy of Orthopaedic Surgeons, Rosemont, IL, pp. 301–312.

Griffin, M.J., 1990. Handbook of Human Vibration. Academic Press, London.

Griffin, M.J., 1997. Measurement, evaluation, and assessment of occupational exposures to hand-transmitted vibration. Occupational and Environmental Medicine 54 (2), 73–89.

Griffin, M.J., Bovenzi, M., Nelson, C.M., 2003. Dose-response patterns for vibration-induced white finger. Occupational and Environmental Medicine 60 (1), 16–26.

Gurram, R., Rakheja, S., Gouw, G.J., 1994. Vibration transmission characteristics of the human hand-arm system and gloves. International Journal of Industrial Ergonomics 13 (3), 217–234.

ISO 8662-7, 1997. Hand-held portable power tools – Measurement of vibrations at the handle – Part 7: Wrenches, screwdrivers and nut runners with impact, impulse or ratchet action. International Organization for Standardization, Geneva, Switzerland.

ISO 5349-1, 2001. Mechanical vibration and shock – Measurement and Evaluation of Human Exposure to Hand-Transmitted Vibration – Part 1: General Requirements. International Organization for Standardization, Geneva, Switzerland.

ISO 5349-2, 2001. Mechanical Vibration and Shock – Measurement and Evaluation of Human Exposure to Hand-Transmitted Vibration – Part 2: Practical Guidance for Measurement at the Workplace . International Organization for Standardization, Geneva, Switzerland.

Kihlberg, S., Kjellberg, A., Lindbeck, L., 1995. Discomfort from pneumatic tool torque reaction force reaction: acceptability limits. International Journal of Industrial Ergonomics 15 (6), 417–426.

Lindqvist, B., 1993. Torque reaction in angled nutrunners. Applied Ergonomics 24 (3), 174–180.

Malchaire, J., Piette, A., Cock, N., 2001. Associations between hand-wrist musculoskeletal and sensorineural complaints and biomechanical and vibration work constraints. The Annals of Occupational Hygiene 45 (6), 479–491.

Palmer, K.T., Haward, B., Griffin, M.J., Bendall, H., Coggon, D., 2000. Validity of self reported occupational exposure to hand-transmitted and whole body vibration. Occupational and Environmental Medicine 57 (4), 237–241.

Pyykkö, I., Färkkilä, M., Toivanen, J., Korhonen, O., Hyvärinen, J., 1976. Transmission of vibration in the hand-arm system with special reference to changes in compression force and acceleration. Scandinavian Journal of Work, Environment and Health 2, 87–95.

Radwin, R.G., Armstrong, T.J., Chaffin, D.B., 1987. Power hand tool vibration effects on grip exertions. Ergonomics 30 (5), 833–855.

Radwin, R.G., VanBergeijk, E., Armstrong, T.J., 1989. Muscle response to pneumatic hand tool reaction forces. Ergonomics 32 (6), 655–673.

Reynolds, D., Angevine, E.N., 1977. Hand-arm vibration, part II: vibration transmission characteristics of the hand and arm. Journal of Sound and Vibration 51, 255–265.

Silverstein, B.A., Fine, L.J., Armstrong, T.J., 1987. Occupational factors and carpal tunnel syndrome. American Journal of Industrial Medicine 11, 343–358.

Sörensson, A., Lundström, R., 1992. Transmission of vibration to the hand. Journal of Low Frequency Noise and Vibration 11, 14–22.

Thomas, M., Beauchamp, Y., 1998. Development of a new frequency weighting filter for the assessment of grinder exposure to wrist transmitted vibration. Computers and Industrial Engineering 35 (3–4), 651–654.

Van Bergeijk, E., 1987. Selection of power tools and mechanical assists for control of occupational hand and wrist injuries. In: Proceedings of American Conference of Governmental Industrial Hygienists: Ergonomics Interventions to Prevent Musculoskeletal Injuries in Industry. Lewis Publishers, Chelsea, Michigan, USA.

Wu, J.Z., Krajnak, K., Welcome, D.E., Dong, R.G., 2006. Analysis of the dynamic strains in a fingertip exposed to vibration: correlation to the mechanical stimuli on mechanoreceptors. Journal of Biomechanics 39, 2445–2456.

Xu, Z., Ding, H.C., Ding, M.P., 1989. A study of dose–effect relationships for vibration induced white finger. In: Proceedings of the 5th International Conference on Hand-arm Vibration, Kanazawa, Japan, pp. 305–308.