FINAL PROGRESS REPORT

November 29, 2014

Grant Number: 5R01 OH008997

Project Title: Glove and Tool Intervention to Reduce Hand-Arm Vibration

Project Period: September 1, 2009 - August 31, 2014

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List of Terms and Abbreviations

A(8)	the root-mean-square averaging of the acceleration signal in units of m/s^2
A_{hw}	frequency weighted root mean square (rms) acceleration
ANSI S.270, 2006	the American National Standards Institute equivalent of ISO 5349.1
AV	anti-vibration
BB	bucking bar - a tool used to absorb impact and vibration in the riveting process
HAVS	hand arm vibration syndrome
DEAV	Daily Exposure Action Value (ISO and ANSI) 2.5 m/sec^2
DELV	Daily Exposure Limit Value (ISO and ANSI) 5.0 m/sec^2
FFT	Fast Fourier Transform
ISO 5349.1, 2001	the ISO standard for measuring and controlling segmental vibration from power tools
HAV	hand arm vibration
ISO 10819, 2013	the ISO standard for evaluating anti-vibration gloves
M,H	mid (M) and high (H) frequency ranges specified in ISO 10819
mV	millivolt
m1	method 1 for measuring TR
PA	palm adapter
PATH	Position Activity Tools and Handling
PSD	Power Spectrum Density
TR	the transmissibility reduction factor of anti-vibration gloves and materials
V	volt
X,Y,Z	coordinate axes for vibration measurement

Formulae and Definitions

DEAV and DELV

$$a_{\text{hUW}} = \sqrt{\sum_i (a_{\text{h}i})^2}$$

$$a_{\text{hW}} = \sqrt{\sum_i (W_{\text{h}i} a_{\text{h}i})^2}$$

a_{hUW}	is the r.m.s. single-axis acceleration value of the frequency-unweighted hand-transmitted vibration, in meters per second squared (m/s²)
a_{hW}	is the r.m.s. single-axis acceleration value of the frequency-weighted hand-transmitted vibration, in meters per second squared (m/s²)
$W_{\text{h}i}$	is the weighting factor for the *i* th one-third-octave bands
$a_{\text{h}i}$	is the r.m.s. acceleration measured in the *i* th one-third-octave bands, in meters per second squared (m/s²)

$$T_{v(\text{DEAV})} = \frac{50}{a_{\text{hv}}^2} \qquad T_{v(\text{DELV})} = \frac{200}{a_{\text{hv}}^2}$$

Abstract

This study involved the pairing of anti-vibration (AV) tools and gloves to optimize the reduction of transmission of vibration to the hands of production workers using pneumatic tools. The project involved several different components: 1) laboratory and field determinations of optimized exposure reduction; 2) assessing exposure conditions in the work environment by developing specialized data logging instrumentation; 3) developing specialized tactometry to assess exposure effects on sensory organelles in the fingertips; and 4) combining laboratory and field assessments to make recommendations on the optimal selection of tools and protection. The project also included an implicit evaluation of the utility of the ISO vibratory assessment standard (ISO 5349.1, 2001) and its glove testing standard (ISO 10819, 2013). While it was understood that the existing standards would be followed for testing, the extent of this work provided an opportunity for assessing the accuracy and utility of the international standards.

The field component of this project was based at two industrial manufacturers, an appliance maker in Iowa and an aerospace defense contractor in Connecticut. Thirty-five different tools were assessed for their vibratory characteristics. In addition, testing was conducted with 8 commercial gloves, 4 materials suitable for glove manufacture, and one prototype glove designed in our laboratory.

The AV glove studies were conducted in concert through cooperative agreement with the Engineering & Control Technology Branch National Institute for Occupational Safety and Health Morgantown, West Virginia 26505, USA. The NIOSH component of this study provided a basis for comparing 1-D and 3-D vibration simulations, and produced parallel conclusions on the importance of axis and grip and contact characteristics.

Important findings included the lack of utility of AV gloves for digital protection from vibration, and major flaws in the ISO glove testing standard (ISO 10819, 2013) as an estimator of risk. Important outcomes were the development of specialized data loggers and finger sensors, and a field tactometer that offered cost and portability advantages over current models.

Aims 1-3 of this study were successfully completed with useful results. Aim 4 was only partially completed. The final field component was truncated because of barriers at the two established study sites in the final year of the project. These barriers included a change in production design and priorities at the appliance manufacturing site, and failure to negotiate an acceptable non-disclosure agreement between the University and the defense contractor site.

Section 1

Significant (Key) Findings

There is an essential incompatibility between the two ISO standards that are involved in AV glove testing -- ISO 5349.1 (2001) which addresses vibratory tool measurement and control and ISO 10819, 1996 (2011) which addresses the transmissibility determination of gloves.

ISO 10819 (2013) -- mechanical vibration and shock — hand-arm vibration — measurement and evaluation of the vibration transmissibility of gloves at the palm of the hand -- is likely insufficient for two reasons. First, the palmar sensor used to evaluate reduction in vibration transmission is limited by the exclusion of the fingers as loci of measurement. Second, the variations in finger grip appear to alter transmissibility in ways that indicate either no effect or amplification of vibratory exposure to the digits. That has important ramifications for glove design, as most tissue from hand arm vibration injury is believed to occur in the fingers.

The replacement of higher magnitude tools with anti-vibration tools, particularly in skilled metal working, fundamentally reduces exposure risks, particularly if administrative controls are used to moderate continuous grinding. As a consequence, given the general diffidence of workers towards the use of anti-vibration gloves, due to problems of hand dexterity with small tools, and given the limited exposure to the palm with small precision tools, the additive value of AV gloves in many settings appears to be negligible. Anti-cut materials such as Kevlar offer a functional alternative to AV gloving in specific settings, because of superior protection against cuts.

Translation of Findings

A new field tactometer was designed in the laboratory and has been tested for field use (Yu and Brammer, 2014). A mounting contact mechanism was developed that offered the same performance as a full surround, but was considerably more flexible for paid field use.

3-D printing was utilized for sensor design at the palm in a process that simplified production and lowered costs, compared to ISO 10819 (2013) recommended materials. Performance characteristics proved to be superior to recommended conventional materials and machining.

A data logger with both hand force and vibration channels was developed for this project. It was successful in limiting noise and power related artifacts that have hampered work in the field. Its characteristics and performance have been presented (Knapp et al., 2012).

Outcomes/Impact

Measuring the impact from the bucking bar (BB) has been a formidable problem for vibration research. The BB had the highest exposure magnitudes of any tool component tested. In this study, it was the only tool that posed significant health risk, based on ISO 5349.2, 2001. This specific adapter for measuring BB stimuli is, to our knowledge, that first of its type capable of generating a flat response. While the specific problem of accurately assessing the riveting/BB operation has very specific and limited industrial applications, the approach and design offers a new and effective tool for industrial hygienists and safety personnel.

Other outcomes and impacts may be more notable for emphasizing uncertainty. The study clearly demonstrates the discontinuity between recommended exposure measurement (ISO 5349.1, 2001) and health protection (ISO 10819, 2013). Accordingly, the results put into question the standard ways of measuring AV effectiveness from gloves and provide evidence that for some processes and tools, gloves may do more harm than good.

The results are not, however, nihilistic. Although a single AV glove regimen cannot be recommended based on this data, there is evidence that effective exposure control is feasible and practical, when it combines engineering controls (low vibration tools), with organization interventions (decreasing or diluting exposure time), and with selective use of gloving.

Section 2 - Scientific Report

Specific Aims

There were four initial Aims:

1. Combining the effectiveness of AV tools and gloves by optimally reducing frequency specific transmission to the hand
2. Measuring health risk reduction by accurately measuring effective exposure reduction throughout the workday by data logging
3. Measuring health risk reduction by accurately measuring post workday temporary threshold shifts (TTS) in vibrotactile perception thresholds of fingertip mechanoreceptors
4. Joining laboratory and field activities to develop a practical and implementable approach to selecting AV tool and glove combinations

Methods and Results

Of the four Aims, the predominant field and laboratory effort was directed to Aim 1. Aims 2 and 3 were principally directed to device development. The devices that were developed – a specialized data logger, sensors and tactometer – were significant outputs from this project with broader relevance to vibration related studies. The mapping of reproduction of tool signatures, the testing of AV gloves and materials, and the coupling of optimized glove tool combinations were the substance of Aim 1, and the heart of the project. Aim 4 was incomplete, due to the withdrawal of the testing sites in the final period of the project.

Aim 1. Combining the effectiveness of AV tools and gloves by optimally reducing frequency specific transmission to the hand

In order to understand the applications of the findings from *5R01 OH008997 Glove and Tool Intervention to Reduce Hand-Arm Vibration,* it is important to review the two ISO standards that address vibratory tool measurements ISO 5349.1 (2001) and glove testing ISO 10819 (2013). ISO 10819 and ISO 5349.1 are intrinsically related since ISO 10819 uses the ISO 5349.1 frequency weighting factors (W_h) to calculate glove TR. ISO 10819 introduces two weighting curves (M and H; M=25-200 Hz and H=200-1250 Hz) to accentuate the key frequency ranges where AV gloves are expected to be maximally effective (>150 Hz). Accordingly, while ISO 5349.1 covers a frequency range of 6.3-1250 Hz, ISO 10819 excludes frequencies under 25 Hz and imposes a different weighting scheme. This has several consequences which are identified below.

<u>Tool Signatures and Exposure Risk</u>

Figure 1 represents tool signatures from the defense contractor site. The presentation assumes an extreme case of 1000 cycles in the course of the working day. Given that the most intense exposure was associated with riveting (riveter and BB) and that operating time has been reduced to a daily maximum of 1-2 hours, this represents a purely hypothetical exposure situation. Only the BB exceeds the DELV of 5.0 m/sec^2. Riveters and BB's fell between the DEAV of 2.5 m/sec^2 and the DELV of 5.0 m/sec^2. It should be noted that the employer realized the concentration of exposure magnitude in the riveting/BB monotask, and in the course of this study there was an active process of diluting riveting/BB applications by distributing them more broadly throughout the hourly workforce. While not the immediate goal of the study, this evolving pattern of administrative control actually reduced exposures below the DELV, thus vitiating some of the necessity of AV glove use.

Figure 1

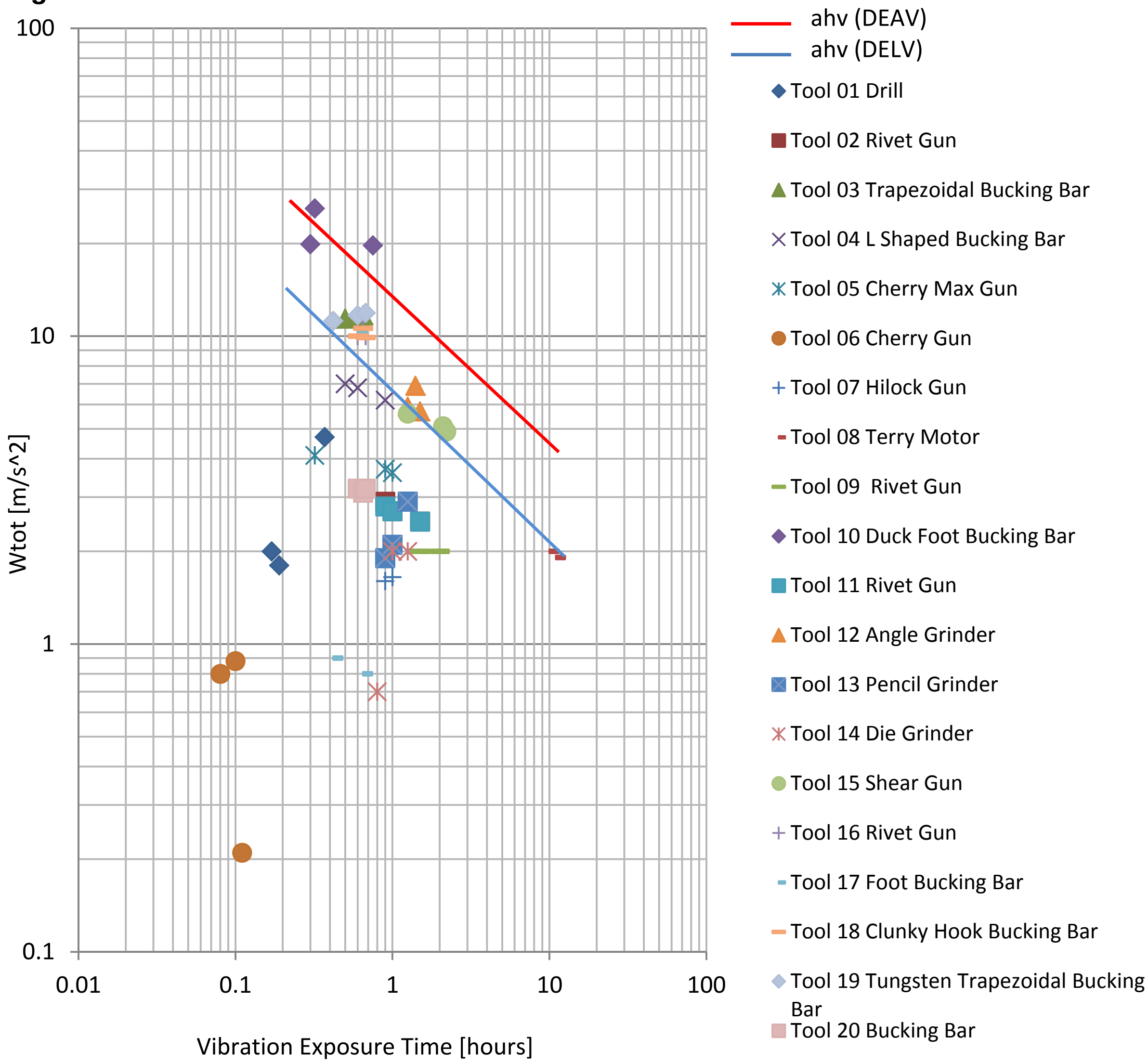
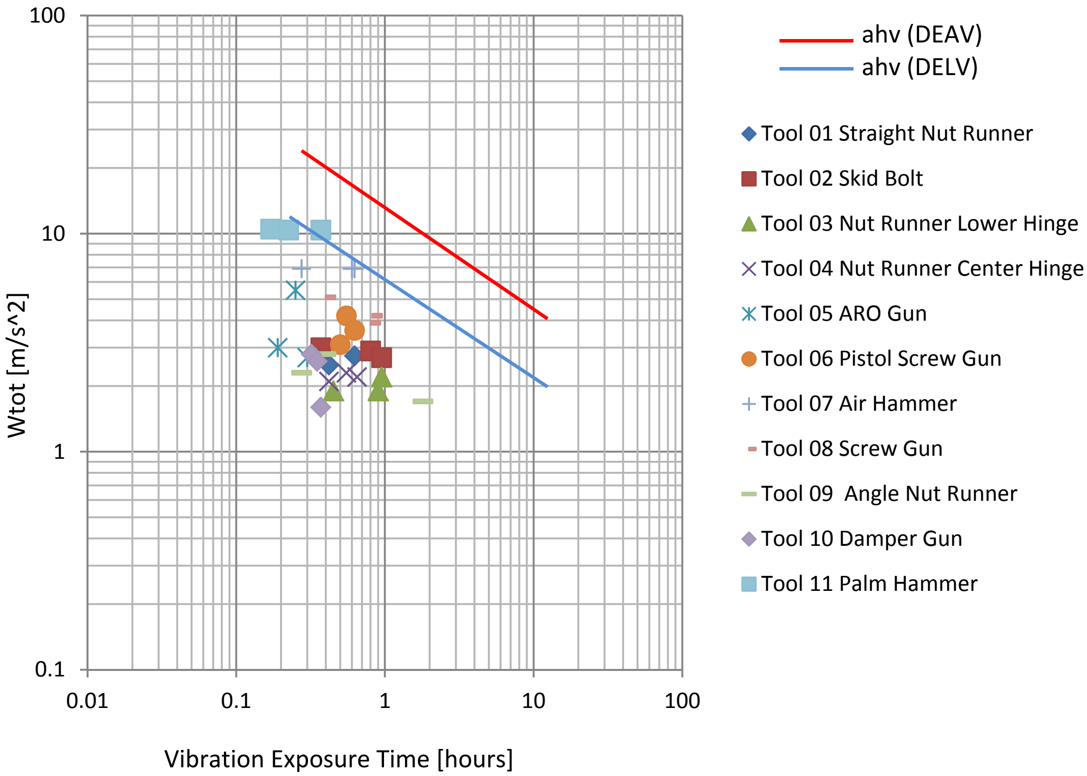


Figure 2 comes from tool evaluation at the appliance manufacturer site. Because of effective tool selection of low vibration tools, it is notable that the facility was already below the ISO action level (DEAV of 2.5 m/sec^2), and would not have required an active program within the European Union.

The results are not inconsequential. In the original proposal, we had planned to replace high magnitude vibration tools with AV tools as an incentive to participating employers and for the ethical reason that we would not conduct a study where there were known and non-addressed health risks. As it turned out, this proved to be unnecessary because exposures were already sufficiently low to discourage immediate mitigation. The comparison of the two sites, offers another important area of observation. The dilution of the riveting process precluded most exposures from posing a recognized human health hazard from vibration. The work process was more continuous at the appliance manufacturer but tool exposures were low, thus obviating the utility of tool-glove interventions.

Figure 2



Glove Testing

Table 1 provides a description of the 9 commercial gloves used in the study. It should be noted that cut and abrasion protection was a key safety concern at both facilities, which is why Kevlar gloves were included in the testing regimen.

Table 1

Test ID	Manufacture and Model	Color	Material Information
Glove 1	Impact, BG413A	White	Air bladder
Glove 2	Impact, BG650A	Yellow	Air bladder
Glove 3	Impact, Blackmaxx Pro	Black	Chloroprene rubber coated
Glove 4	Camelbak, Impact CT	Black	Eva foam
Glove 5	Ansel, HyFlex 11-500	Yellow	Kevlar liner Nitrile foam coated
Glove 6	Ansel, HyFlex 11-511	Green	Kevlar liner Nitrile foam coated
Glove 7	Ansel, HyFlex 11-624	Silver	Dyneema and Lycra liner Polyurethane coated
Glove 8	Ergodyne, Proflex 9002	Black	Nu^2O_2 Polymer
Glove 9	Ergodyne, Proflex 900	Black (half finger)	Visco-elastic gel polymer
Hand 1	NO Glove		

Table 2 demonstrates the TR factor for each of the commercial gloves and the bare hand (non TR control), as recorded by the palm adapter (PA) using Method 1 (M1). For purposes of clarification, M1 was one of three methods used to assess TR. The three measurement methods used to assess vibration transmissibility were: Method 1 (M1), Method 2 (M2) per

ISO 10819 (2013) standard, and Method 3 (M3) as reported by Dong et al. (2002), also known as total vibration transmissibility (TVT).

Using the M1 transmissibility calculation the accelerations are equal to:

$a_h(f_i)=a_{adapter}(f_i)=a_{output(z)}(f_i)$ Eq.1
$(f_i)=(z)(f_i)$ Eq.2,
where $a_{handle}(f_i)$ and $a_{adapter}(f_i)$ are the output accelerations measured in the z-axis only and the $a_{reference}(f_i)$ is the input acceleration also measured in the z-axis only.

Using the M2 transmissibility calculations the accelerations are equal to:

$a_{handle}(f_i)=a_{adapter}(f_i)=\sqrt{a_{output(x)}2(f_i)+a_{output(y)}2(f_i)+a_{output(z)}2(f_i)}$ Eq.3
and $a_{reference}(f_i)=a_{input(z)}(f_i)$ Eq.4,
where $a_{handle}(f_i)$ and $a_{adapter}(f_i)$ are the output accelerations measured as a root-sum-square of acceleration values in x, y and z-axis and the $a_{reference}(f_i)$ is the input acceleration measured in the z-axis only.

Using the M3 transmissibility calculations the accelerations are equal to:

$a_{handle}(f_i)=a_{adapter}(f_i)=\sqrt{a_{output(x)}2(f_i)+a_{output(y)}2(f_i)+a_{output(z)}2(f_i)}$ Eq.5
and $a_{reference}(f_i)=\sqrt{a_{input(x)}2(f_i)+a_{input(y)}2(f_i)+a_{input()}2(f_i)}$ Eq.6,
where $a_{handle}(f_i)$ and $a_{adapter}(f_i)$ are the output accelerations measured as a root-sum-square of acceleration values in x, y and z-axis and the $a_{reference}(f_i)$ is the input acceleration measured also as root-sum-square of acceleration values in x, y and z-axis.

The TR is in the Z-axis (the principal axis for the BB), where the laboratory generated stimulus follow the M and H frequencies. Overall there is modest TR reduction at the palm, except for the air bladder gloves, which are comparatively more effective.

Table 2

	M (25 - 200 Hz)		Pass: < 0.90			H (200 - 1250 Hz)		Pass: < 0.60		
PA-M1	Max	Min	Mean	S.D.	C.V.	Max	Min	Mean	S.D.	C.V.
Glove 1	0.850	0.683	0.764	0.059	0.077	0.744	0.527	0.664	0.062	0.094
Glove 2	0.885	0.744	0.810	0.044	0.055	0.893	0.562	0.670	0.081	0.121
Glove 3	0.948	0.715	0.851	0.077	0.090	0.995	0.502	0.797	0.162	0.203
Glove 4	0.972	0.897	0.947	0.020	0.021	1.121	0.979	1.028	0.041	0.040
Glove 5	0.987	0.959	0.977	0.008	0.008	1.028	0.973	1.004	0.014	0.014
Glove 6	0.982	0.939	0.971	0.010	0.011	1.011	0.969	0.993	0.011	0.011
Glove 7	0.990	0.949	0.976	0.010	0.010	1.047	0.994	1.012	0.015	0.015
Glove 8	0.881	0.529	0.813	0.083	0.102	0.967	0.488	0.805	0.102	0.126
Glove 9	0.938	0.794	0.876	0.042	0.048	1.033	0.818	0.954	0.056	0.059
Hand	1.010	0.945	0.984	0.015	0.015	1.071	0.933	0.992	0.030	0.030

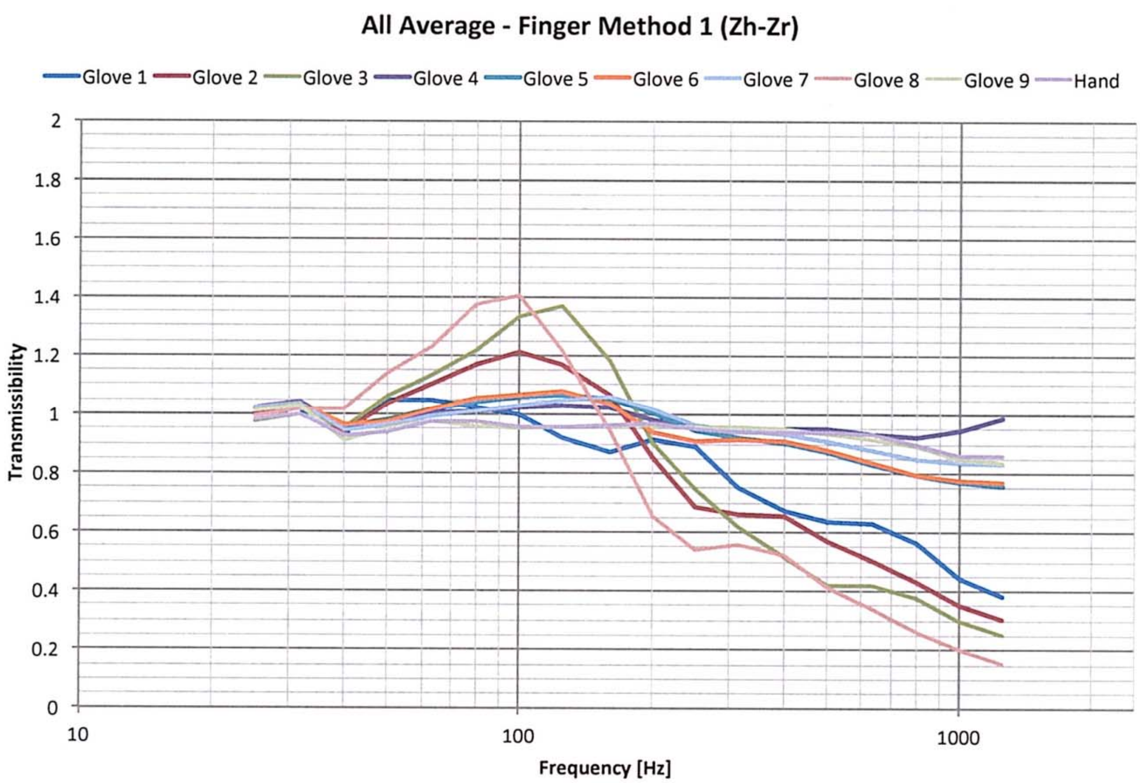
The same approach to the ring adapter showed no reduction up to 200 Hz with some specific effects in the H scale. These findings for finger acceleration raise a core question around ISO 10819 (2013) which involve its application when one of the two scales is satisfied. In Table 3, the Ergodyne fingered glove offers protection in the H scale, but not for the M scale.

Table 3

RA-M1	Max	Min	Mean	S.D.	C.V.	Max	Min	Mean	S.D.	C.V.
Glove 1	1.100	0.846	0.982	0.086	0.087	0.976	0.574	0.775	0.125	0.162
Glove 2	1.266	0.851	1.070	0.130	0.121	0.840	0.477	0.673	0.103	0.153
Glove 3	1.367	0.891	1.136	0.151	0.133	0.844	0.457	0.653	0.115	0.177
Glove 4	1.025	0.976	1.006	0.015	0.015	1.010	0.879	0.955	0.044	0.046
Glove 5	1.122	0.977	1.025	0.033	0.033	1.003	0.725	0.918	0.082	0.090
Glove 6	1.113	0.964	1.020	0.038	0.037	0.967	0.742	0.897	0.074	0.082
Glove 7	1.068	0.949	1.015	0.030	0.029	1.023	0.830	0.945	0.068	0.071
Glove 8	1.353	0.894	1.131	0.164	0.145	0.672	0.320	0.526	0.106	0.202
Glove 9	1.015	0.927	0.967	0.030	0.031	1.017	0.779	0.947	0.062	0.066
Hand	1.028	0.800	0.966	0.056	0.058	1.001	0.735	0.943	0.068	0.072

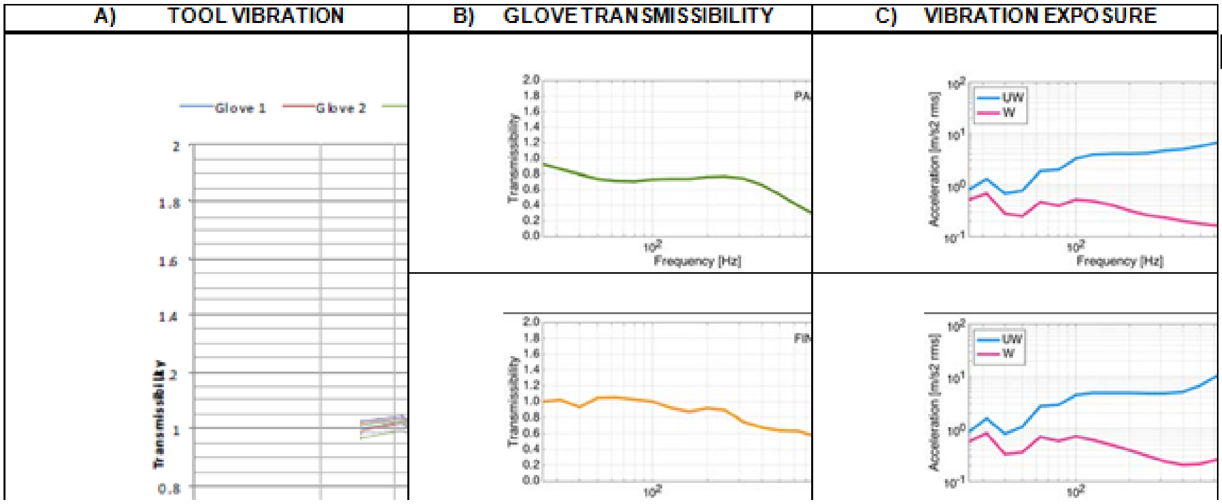
One implication is that if a weighted scale is used that discounts frequency contributions to disease that exceed 200 Hz, then no finger protection is effective through fingered gloves. As Figure 3 shows, the tendency towards amplification at 100-200 Hz with most of the selected gloves raises the question of whether actual harm may be done by finger “protection”. This is presumably due to the changes in grip characteristics that are the consequence of ‘clumsy’ fingered gloves.

Figure 3



The limitations of ISO 10819 (2013) are further demonstrated in Figure 4 and Table 4. The results are for a rivet gun and a leather air-bladder glove for both palm and finger, where column A is the measured spectrum of tool vibration, column B is the ISO 10819 (2013) spectrum of glove transmissibility (from palm and finger adapters), and column C is the calculated spectrums of vibration exposure. Table 4 provides the summary of the total unweighted and weighted accelerations for both tool vibration and vibration exposure (ISO 5349.2, 2001; ISO 10819, 2013), as well as the overall percent reduction in vibration exposure resulting from wearing a leather air-bladder glove while using a rivet gun.

Figure 4



<u>Effectiveness of Air-bladder Glove in Reducing Tool Exposure from a Rivet Gun</u>

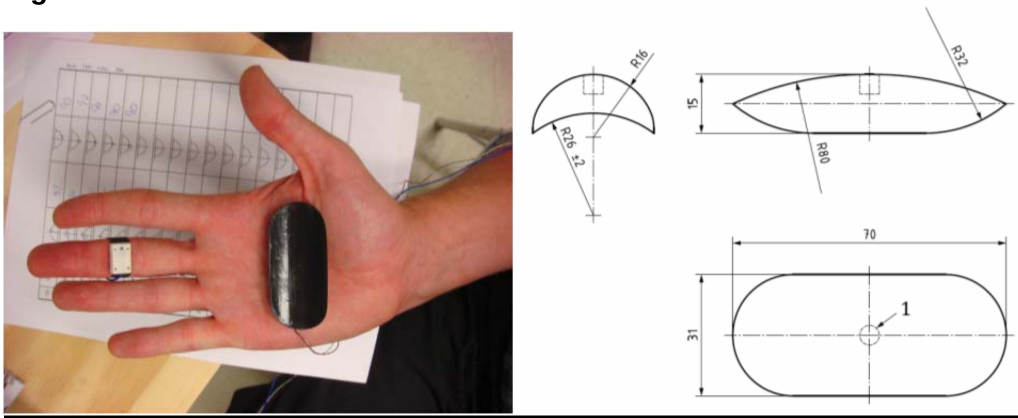
Table 4

Total UW and W Accelerations and Percent Reductions of Tool Vibration and Vibration Exposure					
	Tool (25 to 1,250 Hz)	**Vibration Exposure (25 to 1,250 Hz)**			
		Palm		**Finger**	
	Acceleration [m/s2]	Acceleration [m/s2]	% Reduction	Acceleration [m/s2]	% Reduction
UW	99.2	20.5	79.4 %	43.8	55.8 %
W	2.3	1.5	33.1 %	2.0	13.7 %

While the mean transmissibility values for the M and H spectrums are beneficial for categorizing AV gloves for manufactures, these values do not provide any simple practical use for glove users. Other investigators who saw some effectiveness for AV gloves (Dong et al., 2002; Griffin, 1998) used different glove evaluation methodologies but their results were still limited to the M and H spectrum frequency ranges. In addition, most gloves do not pass the ISO 10819 (2013) M and H tests even though the gloves may still have some practical vibration attenuation capabilities as is evidenced in the calculation of the overall percent reduction in vibration exposure.

<u>Hand and Finger Adapters</u>
ISO 10819 (2013) only stipulates the use of a palm adapter. However, there has been significant data generated from 1996 that documents the principal absorption of vibration from hand tools into the fingers, thus reducing the primacy of the palmar measurement. For this study, a finger adapter was designed to complement the palm measurement. In order to derive appropriate size and mass (<15 gm) characteristics, the sensors were manufactured using polyactic acid polymer and 3-D printing (fused deposition modeling). Figure 5 and Figure 6 present the dimensions of the sensors and their image.

Figure 5



The importance of adapter/sensor design rests on the non-introduction of artifact for transmissibility reduction attributable to the senor/adapter, under the designed frequency range.

For these laboratory studies, a band-limited random vibration signal from 25 to 1,600 Hz, as defined in ISO 10819 (2013), was used for all tests and palmar transmissibility was obtained following the methods outlined in the standard. Finger pad transmissibility was also obtained and was structured to follow the frequency range and calculations used for the palm. Figure 6 demonstrates typical palm and finger adapter transmissibility without gloves using the bare hand. As the Figure 6 demonstrates, both the ring and palm adapters were consistent with ISO 10819 (2013) requirement that TR fall between 0.95-1.05.

Figure 6

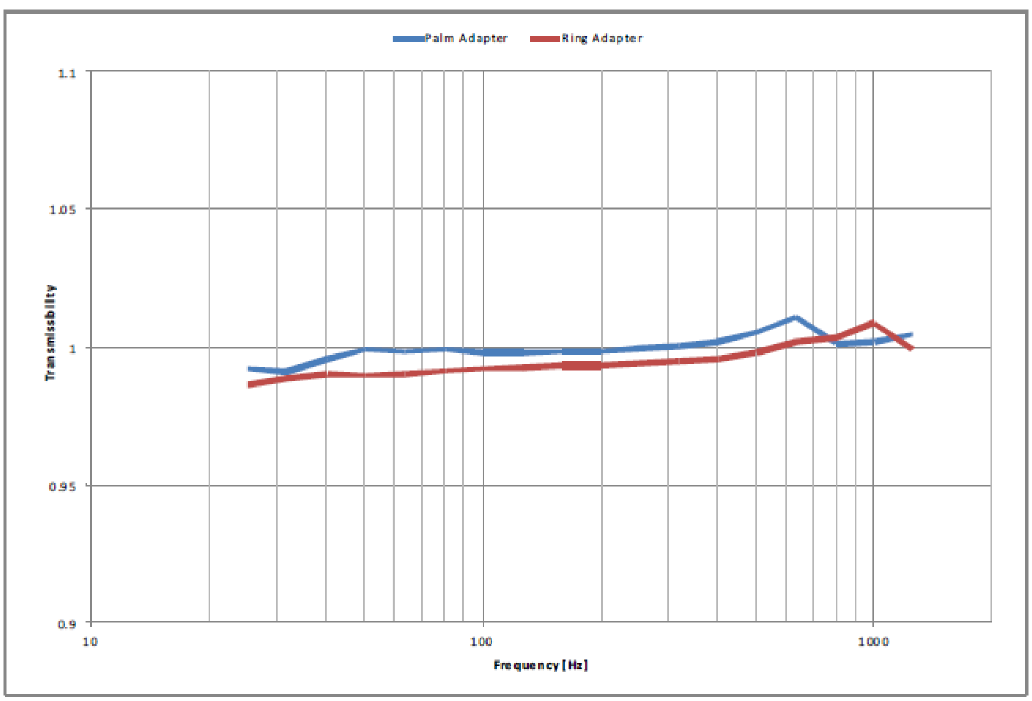


Figure 7 and Figure 8 provide an illustration of TR for the palm and the finger.

Table 5 summarizes TR values for M and H frequency and presents the pass/fail result for each glove consistent with ISO 10819 (2013). To clarify, TRM < 1.0 and TRH < 0.6, where TRM is the overall transmissibility of vibration using the M spectrum [31.5 Hz -200 Hz] and TRH is the overall transmissibility when using the H spectrum [200 Hz - 1 kHz].

Figure 7

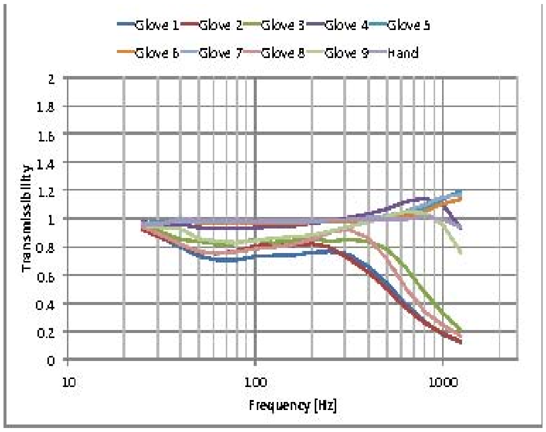


Figure 8

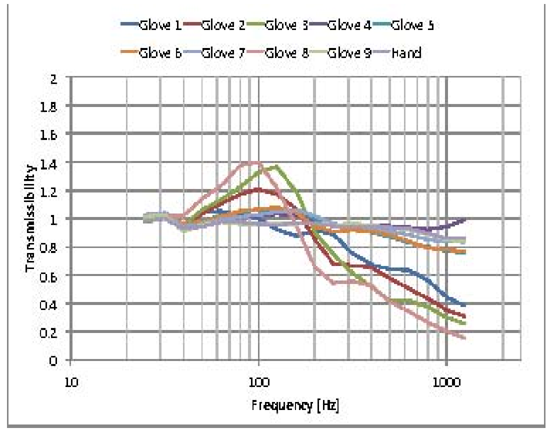


Table 5

Summary of Tested Vibration Attenuation Gloves and Results

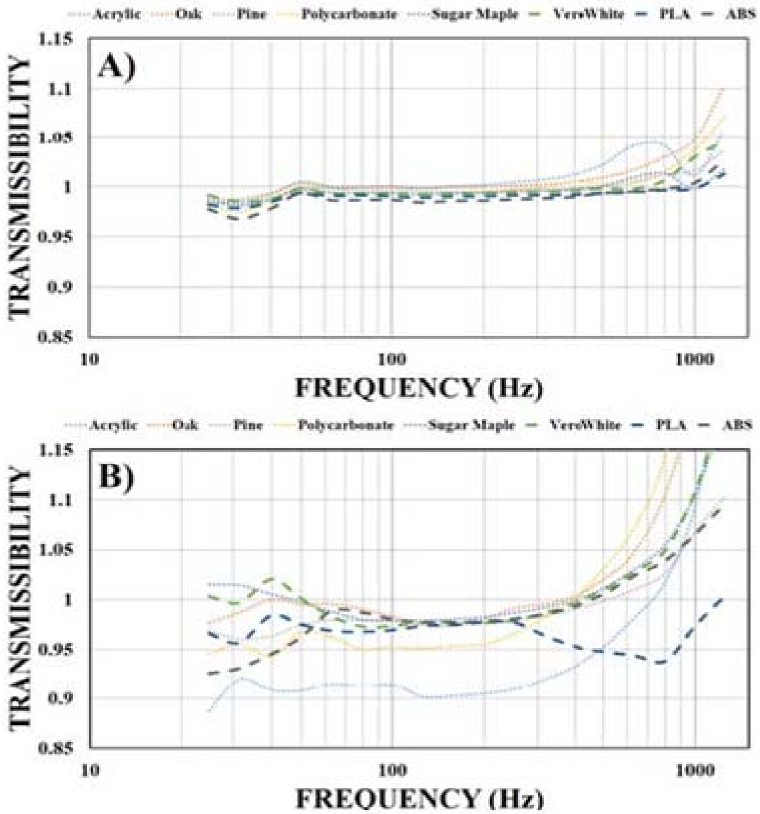
	Glove Material(S)	Glove Type	Palm		Finger	
			M Spectrum(Pass: < 0.90)	H Spectrum(Pass: < 0.60)	M Spectrum	H Spectrum
1 2 3 4 5 6 7 8 9	Air bladder, Pearl leather palm, Lycra back Air bladder, Leather Chloroprene rubber coated, Nylon/cotton knitted liner Eva foam padded, Synthetic leather palm, Spandex back, Nitrile foam coated, Kevlar liner Nitrile foam coated, Kevlar liner Polyurethane coated, Dyneema and Lycra liner Nu2O2 polymer padded, Pigskin leather Visco-elastic gel polymer padded, Pigskin leather	Full finger Full finger Full finger Full finger Full finger Full finger Full finger Full finger Half finger	0.764 0.810 0.851 0.947 0.977 0.971 0.976 0.813 0.876	0.6640.6700 .7971.0281. 0040.9931.0 120.8050.95 4	0.982 1.070 1.136 1.006 1.025 1.020 1.015 1.131 0.967	0.775 0.673 0.653 0.955 0.918 0.897 0.945 0.526 0.947
Bare Hand	Reference		0.984	0.992	0.966	0.943

The findings add to the problems already cited on AV glove effectiveness and TR measurement. Although Gloves 1, 2, 3, and 8 are marketed as AV gloves, their effectiveness was only confirmed within M spectrum and not within the H spectrum. Air bladder gloves (Gloves 1 and 2) were very close to the standard's threshold value of 0.6 for the H spectrum but were observed to not quite meet this requirement, which is in agreement with other previously reported glove studies done as part of this project (Welcome et al., 2012; Welcome et al., 2014). Finger transmissibility for all gloves varied from that of the palm, where the transmissibility at the M spectrum for the palm indicated appropriate attenuation in some gloves but for none of the gloves at the finger, where amplification was also observed. These results suggest that glove transmissibility measurements taken only at the palm can incorrectly characterize the ability of a glove to attenuate vibration and mitigate exposures to the entire hand. These results also suggest that ISO 10819 (2013) transmissibility measurements taken at the finger are feasible and should be strongly considered in a future revision of this standard. They further confirm the findings described in the previous section on Glove Testing.

An additional outcome of this work was the provision of evidence that adapter production could be simplified by 3-D printing techniques. The current ISO standard for glove testing (ISO 10819, 2013) recommends the use of rigid materials; however, the complex surface geometry and a misleading technical drawing of the palm adapter requires advanced manufacturing capabilities in order to meet the dimensions, weight, and transmissibility constraints.

Figure 9 compares bare handed (A) and tourniquet bound (B) testing methods using recommended and other commonly used materials. The 3-D printing materials (PLA and ABS) provided the flattest frequency response of all materials and methods in both tests.

Figure 9



Tourniquet-mounted palm adpater (A) and bar hand palm adapter (B) transmissibilities.

Additive manufacturing methods used to generate palm adapters are time and cost efficient and, if universally adopted, promote a consistent construction of the ISO palm adapter and may help to minimize the variation in glove testing results observed between testing facilities. In addition, the reduced weight of the 3D printed palm adapter may also minimize measurement error, since heavier adapters may yield incorrect values due to a higher apparent mass, especially when coupled with thicker material gloves. Also, 3D printing allows for a quick adjustment and manufacture of palm adapters with various profile radii in order to better interface thicker or thinner gloves tested with the 40 mm diameter ISO 10819 (2013) handle and provide a uniform contact area and more consistent results.

Riveting and Bucking Bar Adapter

Riveting is a 2-person process where one worker applies the rivet and a second absorbs impact and vibration with BB. Although vibration from a riveter is easily measured, because of the accessibility of the handle, the BB is frequently inaccessible and only has minimal surface contact which has historically complicated its measurement. Figure 10 is a photograph of the 5 BBs most commonly used at our defense contractor site. Figure 11a is a presentation of the adapter and a demonstration of its successful filtering of percussion in BB measurement. The adjacent Figure 11b shows the transmissibility function of the adapter cube which gives a flat response up to 2000 Hz, and was therefore suitable for high impact field measurements. Figure 12 demonstrates the riveting/BB process.

Figure 10

Figure 11a and Figure 11b

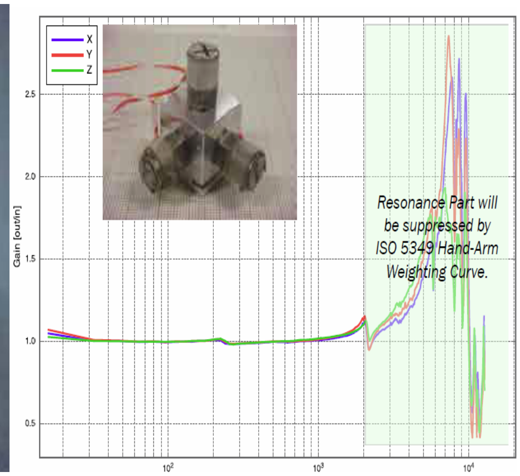


Figure 12

Aim 2. Measuring health risk reduction by accurately measuring effective exposure reduction throughout the workday by data logging

<u>Data Logging Device Development</u>
The field component of this project required the development of a new generation of data loggers suitable for capturing full wave forms over a complete work shift. The purpose was to

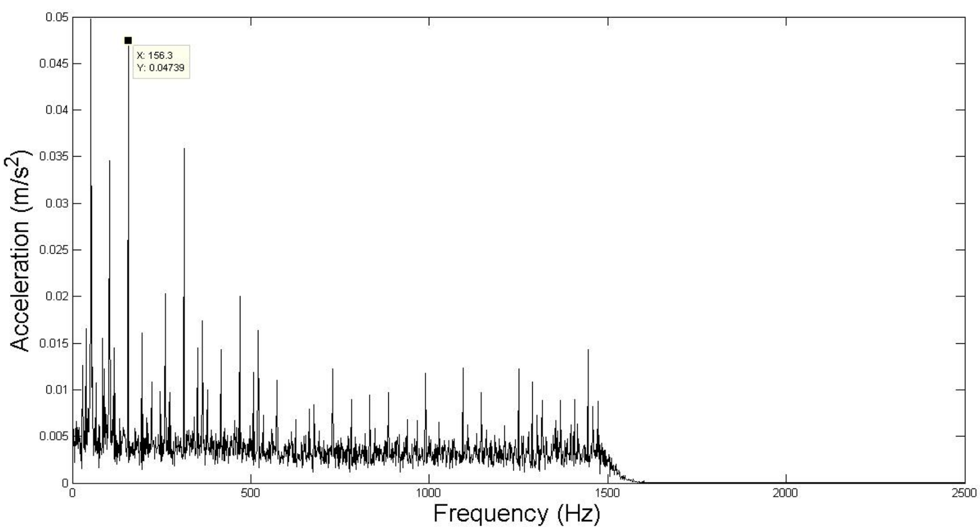
take direct measurements rather than relying on calculations of weighted averages and estimations using predefined standards. A major reason for this more inclusive design was recognition that existing standards and weighting might not prove adequately protective. The success of the data logger was central to glove and material testing to assess their effectiveness as vibration filters. The challenge was to measure forces on the subject as well as accelerations.

The sampling rate of the acceleration channels was designed to be 2000 Hz, higher than comparable electro goniometric systems so that signals with a frequency up to 1000 Hz higher could be recorded. The device was also designed to incorporate higher magnitude signals as it was designed to measure accelerations up to 500 m/s^2. The provision of 6 force and 2 acceleration channels was an accommodation to the observed phenomenon that contact forces vary throughout the hand at the point of tool operation.

The major technical obstacles that required solution went well beyond the electronics. Sampling rates of 40 KHz for the complete set of acceleration channels are very fast; since force channels could not be reduced below 908 Hz there were significant current demands that required both a novel battery configuration, as well as noise reduction. The current system has 8 channels sampling at 5000 Hz and 8 channels sampling at 908 Hz, giving a total of 47,264 Hz. The high data recording rate created significant problems that required resolution involving data block collision. The high sampling rate in the force channels required creation of flags to promote discrete block writing.

Noise reduction also posed a significant technical problem. By enlarging the range of acceleration values, a reduced number of volts could be assigned to represent 1 m/s^2. With a voltage range of 2V, 4 mV represents 1 $ms/^2$ given the finger maximum acceleration of 500 $ms/^2$. Hence the instrument noise needed to be less than 4 mV to provide a dynamic range from 1-500 $ms/^2$. An FFT is shown in Figure 13 of a baseline noise measurement after the battery configuration was changed to provide the desired performance.

Figure 13



Aim 3. Measuring health risk reduction by accurately measuring post workday temporary threshold shifts (TTS) in vibrotactile perception thresholds of fingertip mechanoreceptors

The tactometer designed for this project consists of: 1) a vibration stimulator suspended from a beam balance, the fulcrum of which is mounted on a vertically adjustable track; 2) an arm rest on which the hand and forearm are placed in supination; 3) a small diameter cylindrical probe within a static cylindrical surround through which the stimulus is applied to the skin; 4) an accelerometer and electronics to record the motion at the surface of the skin, and; 5) a computer to administer the stimulus consisting of sinusoidal tone bursts, and calculate perception thresholds. The stimuli consist of short-duration tone bursts. Successive bursts initially increase in intensity until the subject signals, by pressing a switch, that the stimulus has been detected. This action defines the first ascending, or "upper" threshold. Successive bursts then decrease in intensity until the subject signals that the stimulus can no longer be felt, so defining the first descending or "lower" threshold. The burst intensity is then, once again, increased. This cycling of burst intensity is repeated at least four times, and the mean threshold acceleration is calculated from the arithmetic sum of the sequence of ascending and descending thresholds when all thresholds are expressed in dB re 10^{-6} m/s^2 (ISO 13091-1, 2001). The performance of the apparatus is confirmed daily. The challenge for this project was rapid administration at the conclusion of the work shift.

The tactometer utilizes a manual ratchet to lower the probe onto the test fingertip. In order to prevent involuntary and/or vibration stimulated jerks or movements of the test finger, we have introduced a beam balance with the stimulator suspended on a swivel bearing to allow both vertical and horizontal movement of the probe tip. Two strategies were pursued to maintain the desired contact between the probe tip and the skin of the fingertip, and so reduce time lost repositioning the stimulator: a direct measurement of skin-stimulator contact force, displayed to the subject by a series of colored lights; and a static surround, coaxial with the probe, in constant contact with the fingertip. This latter approach was preferred and ultimately selected because the rapid positioning of the stimulator requires considerably less control and error because it involves less precise control of the skin-to-stimulator contact force.

In order to demonstrate the validity of this optimized field approach, it was necessary to test within ISO standards. ISO 13091-1 (2001) provides four alternative configurations for the orientations of the stimulator and finger to determine vibrotactile perception thresholds (VPTs). Two possible configurations involve the stimulator probe contacting the fingertip from below, while the other two have the probe facing down and contacting the fingertip from above. The two configurations with the fingertip contacted from above were compared for field use and are shown in Figure 14. For these, only a probe contacts the fingertip in Method A (left panel in Figure 14), whereas the probe and a surround contact the fingertip in Method B (right panel in Figure 14). In both methods the hand is full supported by an arm rest with the palm facing upwards. The comparative results are presented in Table 6. The equivalence of both methods and suitability for men and women established the utility of Method A for rapid field use.

Figure 14

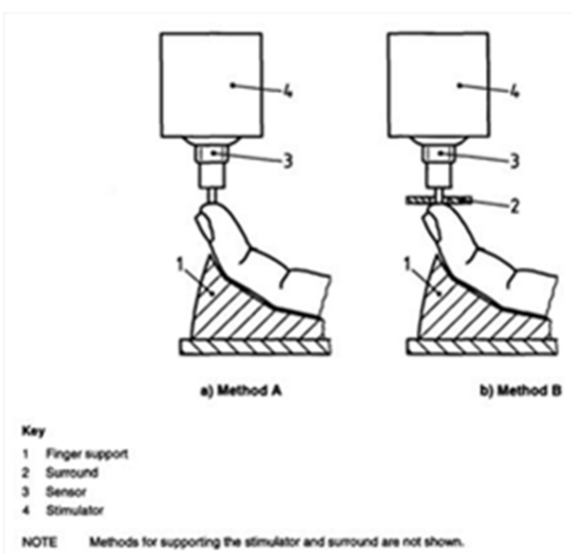


Table 6

Method (A or B)	Measurement Conditions (N.B. All probes & surrounds - circular cross-section)	Mean VPTs (dB re 10-6 m.s-2)				Sex (M or F) [# of fingers]
		4 Hz	20 Hz	31.5 Hz	125 Hz	
A	3 mm probe, no surround; 0.05 N contact force (~0.9 mm indentation); U-D† [data from Ref. 3]	78.8		100.2	(110)	M [n = 99]
B	3 mm probe, 6 mm surround; 0.6 N contact force (~0.5 mm indentation); U-D†	76.0		103.9	112.1	M [n=12]
B	3 mm probe, 6 mm surround; 0.6 N contact force (~0.5 mm indentation); U-D†	76.5	93.9		111.5	M [n=36]
B	3 mm probe, 6 mm surround; 0.6 N contact force (~0.5 mm indentation); U-D†	72.8		101.6	105.6	F [n=40]
A or B	ISO 13091-2 (2003)	77.5	92.3	100.3	107.8	M

Aim 4. Joining laboratory and field activities to develop a practical and implementable approach to selecting AV tool and glove combinations

There were major difficulties in establishing a sufficiently large test sites with vibratory exposures that were of sufficient magnitude to permit significant exposure reduction. In Year 4 of the project, one of the two test sites, the appliance manufacturer suspended its participation, due to a management change, and the conversion of its assembly line to a more automated process. This withdrawal, late in the study process, derailed the expected final phase of tool testing with optimized gloves. We were unable to locate a suitable set of replacement sites due to low numbers of employees and low levels of exposure in New England precision manufacturing. In fact, as noted, the appliance manufacturer exposures turned out to be quite low, thus obviating some of the utility for extensive comparative effectiveness field testing. Nevertheless, considerable information was obtained and is summarized.

Table 7

Straight Nut Runner	Aro Gun
Angle Nut Runner	Pistol Drill
Pistol Nut Runner	Straight Drill
Skid Bolt Gun	IR Air Hammer
Cleco Screw Gun	Palm Hammer
Cleo Damper Gun	

Extensive tool signatures had been obtained on these 11 tools (Table 7). There were, moreover, other limitations with the site that mitigated against successful realization of study hypothesis. As already presented in Tool Signatures and Exposure Risk under Aim 1, exposures were low. In Figure 1, weighted tool signatures are represented with the assumption of 1000 task cycles per shift. The assumption is hypothetical, as it would presume that pneumatic tool use proceeded at 2 cycles per minute. In fact, line speed approaches 2 units per minute, but only a fraction of this time involves tool engagement. Even in this extreme and hypothetical case, measures fall below the DEAV.

The second site, the defense contractor had higher exposures, but it was also problematic, due to security concerns. In 2012, a non-US national member of the study team had done onsite testing at Sikorsky Aircraft Corporation. Sikorksy's internal security had apparently allowed him into areas that were restricted for foreign nationals. An investigation delayed the study process by 6 months. Once resolved, a second security problem arose. Sikorsky and our host institution, UConn Health Center began an involved dialogue on a revised non-disclosure agreement (NDA) in the summer of 2013. To date, Sikorsky has been unable to accept UConn's revised language. We continue to pursue the NDA and will attempt to provide a limited field study on 10-20 participants through the end of 2014.

Because we were unable to complete the final stage of work at the two sites, we consider Aim 4 to be unfulfilled. Accordingly, approximately $92,000 in direct costs and $50,000 in indirect costs were unspent.

One of the practical outcomes of this work at the defense contractor was the issue of characterization of exposure duration. The same presumptions applied as were made at the appliance manufacturing site. The 1000 task cycle assumption is even more outrageous, given the brevity of the process for BB use with riveting, as these are not dedicated tasks. Here the BB does offer potential harmful exposure. However, the ineffectiveness of the AV gloves for the BB limits their use for exposure reduction.

Whether exposure is measured in the time domain of the electronic signature or by time-window sequence is critically important. Figure 1 depicts a waveform from the BB at Sikorsky aircraft. The vibration signals last for 0.000277 hours (< 1 sec). The signals for the right and left hand each exceed a total weighted acceleration value (ahv(rms)R,L) of 15 m/sec2. By direct calculation, the A(8) time weighted average, following ISO 5349.1 (2001), would be ~0.1 m/sec2, a level well below the DELV of 5 m/sec2, as stipulated by the EU Human Vibration Directive 2002/44 EC and ANSI S.270-2006. However, if the observed cycle time of BB use is 50-60 minutes is observed as well as the task sequence of 3.4 seconds, as was typical for actual workplace use, then the A(8) exceeds 5 m/sec2, which exceeds the DELV. It should be noted that this also presents a broader problem in that the epidemiologic studies on which ISO 5349.1 (2001) are based, involve an approximation of observed time and, therefore, the more refined machine measurement introduces non-comparability.

Another implication of the work involves implications of the differences between the exposure standard (ISO 5349.1, 2001) and the AV glove standard (ISO 10819, 2013). Unweighted vibration levels were influenced primarily by the frequency range. However, frequency weighted vibration levels were inert to frequency range because frequency weighting (W_h) offers an implicit adjustment.

Conclusions

While the project was not completely successful in its final field validation, the overall results were highly significant. In particular:

1. There was considerable evidence for the incompatibility of ISO standards:
    a. ISO 10819 (2013)and ISO 5346 were shown to be largely incomaptible with the directions to manufacturers for testing and have limited applicaton to field exposure.
    b. ISO 10819 (2013) by failing to incorporate the element of digital absorption significantly overrated protective factors and downweighted potentially hazardous exposure to the the digits.
2. The overall lack of utility of most AV gloves, even those testing effective, was consistently demonstrated across glove types.
3. Use of lower vibration tools and curtailment of exposure time appear to be effective measures for health protection.

4. The complexities of grip alteration and effects on dexterity call into question the value of fingered AV gloves as recommended in ISO 10819 (2013).
5. The value of injury or cut protection should probably be a priority over AV finger protection.

In short, there is some protectiveness from AV gloves. However, the glove-digit interface, because of biodynamic factors is complex and the current data affirms the amplification effect in the fingers that some investigators have also noted. Practically speaking, in deciding on AV gloves, the level of tool exposure magnitude and hand dexterity and subjective acceptance are at least as important as the AV characteristics of the materials.

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Inclusion of Gender and Minority Study Subjects

Inclusion Enrollment Form attached.

Inclusion of Children

No children were involved in this study.

Materials Available for Other Investigators

The study led to the development of a protocol to assess anti-vibration gloves and the algorithms to produce 3-D palm and finger transducers. Requests for the protocol or algorithm should be addressed to Dr. Donald Peterson at peterson@engr.uconn.edu. A rapid processing field tactometer was constructed. Requests for additional information about the tactometer should be sent to Dr. Anthony Brammer at brammer@uchc.edu.