Riveting Hammer Vibration and Nerve Damage

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Abstract

Hand Arm Vibration Syndrome (HAVS) is an occupational disease affecting 50% of riveting hammer operators after 10 years of work.[1] Current international standards (ISO 5349) seeking to protect workers from occupational vibration are not effectively predicting HAVS onset.[1–3] Scarce research has been done which investigates the long term effects of riveting hammer vibration exposure and nerve regeneration. The present study examines the effects of typical occupational vibrational exposure on cutaneous mechanosensory peripheral nerve populations (lanceolates) and as well as nerve bodies (dorsal root ganglion) that are responsible for nerve regeneration. A piezoelectric sensor-based data acquisition system is used rather than the traditional laser vibrometer. Although data analysis is not complete, current results show that the piezoelectric system is a viable means of vibrational analysis for both laboratory and workplace research. It records dominant kilohertz frequencies in the riveting hammer vibration signal which are currently overlooked by ISO 5349.

1. Introduction

Hand-Arm Vibration Syndrome (HAVS) is a neurodegenerative and vasospastic disease observed in workers who regularly use handheld percussive power tools. In the United States alone, 1.5 million workers are exposed to hand-transmitted vibration.[4] HAVS symptoms include numbness, blanching, and tingling of the fingers as well as loss of fine motor control.[5] Symptoms may be severe enough to warrant a change in occupation.[6]

Past research has shown that the occurrence of HAVS is directly related to the duration and repetitiveness of vibration exposure.[2] Namely, 50% of workers who use pneumatic riveting hammers develop HAVS after 10 years of work.[1] The International Organization for Standardization (ISO) standard 5349 attempts to estimate the risk associated with the operation of handheld power tools. It employs a frequency weighting calculation that claims frequencies <16 Hz are most harmful, while frequencies >160 Hz can essentially be ignored. In contrast, the riveting hammer (among a multitude of handheld power tools) exhibits dominant vibrational energy in the kHz range.[3] In both theory and reality, ISO 5349 severely underestimates the risk of HAVS onset.[1–3]

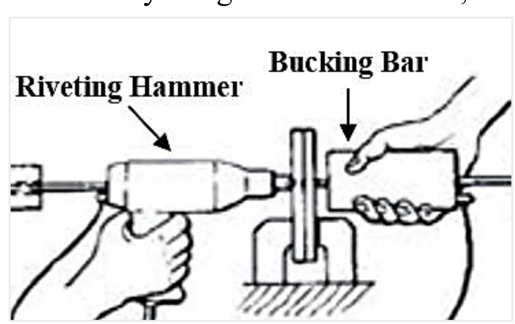

Figure 1: Demonstration of how the riveting hammer and bucking bar are used in unison to set a rivet. (Dandanell and Engstrom, 1986) [1]

The final stages of HAVS are well documented but their onset is not well understood. The permanence of HAVS also increases with vibration exposure duration, but the precise threshold between permanent and reversible damage is unknown.[4] A rat tail model has been developed and produces similar peripheral nerve

[1] The findings described in this paper were financially supported by the Wisconsin Space Grant Consortium (WSGC). The mentorship of Dr. Danny Riley and Mr. James Bain has served as a pivotal foundation for all research described in this article. Additional thanks are given to Dr. John LaDisa of Marquette University for approving this research to serve as the author's undergraduate thesis.

damage in rats to what is observed in workers with HAVS.[4,7] The rat tail model simulates vibration exposure as seen by workers who operate the bucking bar. The bucking bar is a steel bar used with the riveting hammer to set a rivet. Interestingly enough, bucking bar operators experience more high frequency (kHz) vibration and more commonly exhibit HAVS than workers who operate the riveting hammer.[1,7]

Exposure to a single, 12 minute bout of riveting hammer vibration results in mechanosensory nerve destruction when observed 4 days after the delivery of vibration.[2] While acute exposure to riveting hammer vibration has been studied, a long term model replicating occupational exposure has received little to no attention. Nearly all long term HAVS studies used vibrational shakers to deliver vibration, rather than the riveting hammer. Vibrational shakers are capable of delivering single frequencies at limited accelerations, while the riveting hammer vibration signal consists of a wide range of frequencies with varying accelerations. Since workers received regular exposure to riveting hammer vibration, it is necessary to include both of these aspects.

The present study examines the effects of typical occupational vibrational exposure on cutaneous mechanosensory peripheral nerve populations and as well as nerve cell bodies that are responsible for nerve regeneration. The previously developed rat tail model was combined with a novel piezoelectric-based data acquisition method. The recorded vibrational signal was analyzed and interpreted in terms of transmissibility. The nerve damage quantification portion of this study is still underway.

2. Methods

A) Animals. Thirty six female, 5 week old, Sprague Dawley rats were used for this study. All animal handling, testing, and surgery was approved by the Medical College of Wisconsin's Institutional Animal Care and Use Committee (IACUC). The animals were randomly assign to one of the four following groups (n=9):

(1) 5 week control – animals are placed in control restraint for 12 min/day, 5 days/week (Mon-Fri) for 5 weeks, and euthanized on the sixth Monday.
(2) 5 week vibration – animals are placed in vibration restraint for 12 min/day, 5 days/week (Mon-Fri) for 5 weeks, and euthanized on the sixth Monday.
(3) 5 week control with recovery – animals are placed in control restraint for 12 min/day, 5 days/week (Mon-Fri) for 5 weeks. The animals remain in standard vivarium housing for weeks 6-10 and are then euthanized on the eleventh Monday.
(4) 5 week vibration with recovery – animals are placed in vibration restraint for 12 min/day, 5 days/week (Mon-Fri) for 5 weeks. The animals remain in standard vivarium housing for weeks 6-10, and are then euthanized on the eleventh Monday.

The rats were acclimated to the restraint used for 12 minute intervals for 5 days prior to testing. Once rats were loaded into the tubular restraints, both the restraint and the rat's tail were taped securely to the tabletop to fully mimic experimental restraint conditions. Rats were housed overnight in a temperature-controlled vivarium room, and transported daily to the laboratory for testing. Food and water were available ad libitum, except during the 5 minute commute from the housing room to the laboratory

B) Piezoelectric Rat Tail Model. The present, piezoelectric rat tail model is largely derived from the laser vibrometer-based rat tail model used and described in previous studies.[2,3,8] A rat is gently coerced into a PVC tube restraint which is then secured to the nonvibrating platform. The loaded restraint is positioned so that the relaxed, fur-skin interface of the tail aligns with the proximal end of the riveting platform. Masking tape is placed laterally to secure the tail to the riveting platform. This setup is duplicated to form a control restraint and a vibration restraint. Animals belonging to the control group are placed in the control restraint, in which the riveting platform is stationary. Animals belonging to the vibration groups are placed in the vibration restraint, in which the riveting platform is mounted on a vertically-fixed riveting hammer. The vibration restraint is enclosed by a noise attenuation box in order to prevent audial discomfort. The vibration restraint uses two piezoelectric sensors (1 ventral and 1 dorsal) to record the vibrational output of the riveting hammer. An electric timer set to 12 minutes is wired to a voltage dependent airline valve. When a voltage is applied, the airline value opens and allows the pneumatic riveting hammer to operate.

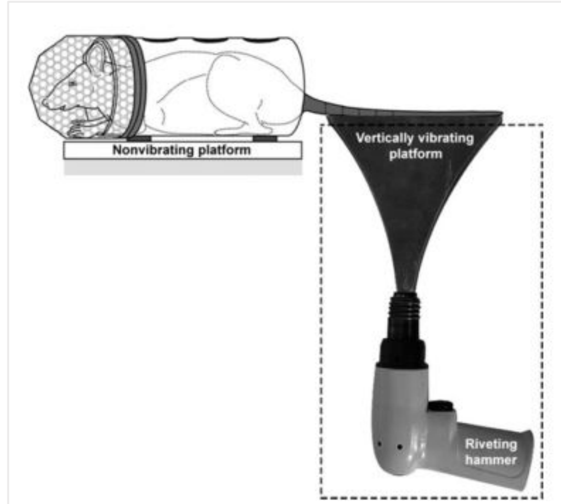

Figure 2: Vibration restraint setup. The dashed line represents the noise attenuation box that encases the riveting hammer portion of the vibration restraint (Raju etal 2011) [2].

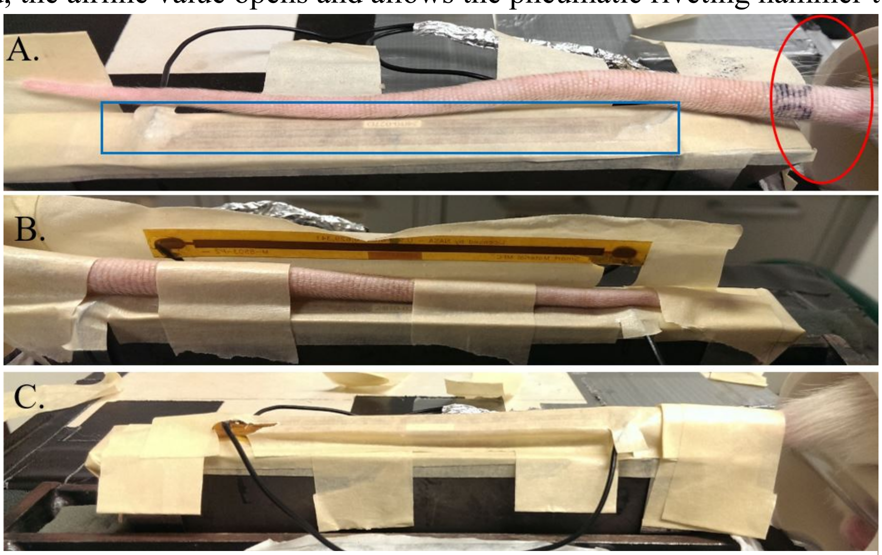

Figure 3: Step-by-step placement of the piezoelectric sensors on the vibration restraint. (A) The rat tail sits relaxed on the riveting platform. Circled in red is the fur-skin interface of the rat tail which is used to align the tail with the riveting platform. Outlined in blue is the ventral piezoelectric sensor. (B) Four tapes are placed laterally before the dorsal piezoelectric sensor is placed. (C) The dorsal piezoelectric sensor is then secured.

C) Piezoelectric Sensors. Two Smart Material Corp. Macro Fiber Composite M8503-P2 (MFCs, or piezoelectric sensors) were used to record the vibrational signal produced by the riveting hammer. Piezoelectric sensors consist of a manmade piezo ceramic sealed between electrodes a polyimide film. When experiencing a load, the stressed piezo ceramic's dipole alignment changes, creating a voltage. The voltage can be measured at the metal contacts due to the internal arrangement of the electrode and conductor layers. The M8503-P2 piezoelectric sensors are able to detect frequencies up to 3MHz, making them ideal for the investigation of the kHz vibrations within the riveting hammer signal. Traditionally, MFC piezoelectric devices have been used to sense and respond to vibrations on satellites and aircraft. To our current knowledge, this is the first study which repurposes the MFCs to record power tool vibration in an animal.

Before placement on the tail, two strands of flexible headphone wire were soldered to each piezoelectric sensor, one strand to each of the two metal contacts. After the newly formed junction was cooled to room temperature, cyanoacrylic glue was used to shield the exposed solder joint and adhere the first 4mm of wire to the piezoelectric sensor in order to alleviate the sensitive solder joint from vibrational stress. Once assembled, the free ends of the piezoelectric sensor wires were clamped into the terminals on the National Instruments (NI) 9222 Analog Voltage Module. The NI 9222 module connects to the NI cDAQ-917 chassis, which then connects to a laptop via USB. A baseline recording is made with both sensors lying flat on the riveting platform.

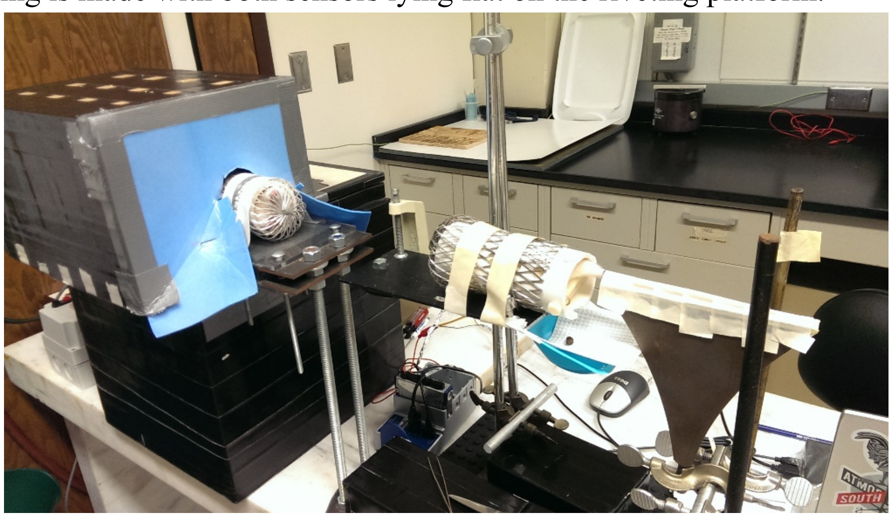

Figure 4: Loaded vibration restraint (left) and loaded control restraint (right). The NI hardware sits beneath the suspended restraints.

Once the sensors are placed on the tail, data collection is initiated when the riveting hammer begins reciprocating for at least 10 seconds. Three or four collections were made per day, resulting in every animal in either vibration group to be recorded once a week. Previous research has shown the riveting hammer vibration signal to contain a maximum frequency of roughly 16 kHz.[3] To sufficiently abide by the Nyquist sampling rate, a sampling rate of 75 kHz was chosen. A custom made Virtual Instrument (VI) was used in NI LabVIEW to record the raw voltage and calculate the power spectrum of the vibrating piezoelectric sensors.

D) Non-survival surgery. A ketamine-based anesthetic cocktail was administered intramuscularly to the rat's left quadricep. The injection site was massaged ooccasionally to encourage the circulation of anesthetic. Surgery began when the animal was no longer responsive to a foot-pinch. Laying dorsal side up, an axial incision was made and held exposed by hemostats. A pneumothorax was performed. The perfusion needle was maneuvered to puncture and rests inside the left ventricle. The right auricle was cut, and the perfusion machine began to pump saline. When clear saline flowed out of the right auricle, fixative was pumped through the animal. Once fixed, the tail and lower spine were excised. The tail segments (C5, C6, C11, C12) and tail tip were excised, chemically fixed, and stored. The lower spine was placed directly into fixative to preserve sensory neuron ganglia.

E) **Tissue processing.** Tail segment C12 was cut into 16 serial, 60 micron sections using a cryostat microtome. Sections underwent immunostaining and were examined under a fluorescence microscope. Lanceolate nerve complexes are mechanoreceptors that surround the hair follicles in the skin of rat tails. Digital images were taken of lanceolates and are currently being quantified as to number and integrity. Degradation of lanceolate complexes would attribute to the symptomatic numbness observed in HAVS.

Dorsal root ganglia (DRG) contain neuronal cell bodies which are vital for the regeneration of sensory nerve fibers. They were dissected from spinal segments S4-6, but are yet to be examined histologically. A reduction in DRG cell count (i.e, cell death) would explain the inability to regenerate nerve fibers. This would then serve as physiological evidence for the permanence of HAVS.

3. Results

The VI recorded the riveting hammer's vibrational signal in both the time and frequency domains. To test the efficacy of the new piezoelectric-based rat tail model, the time domain

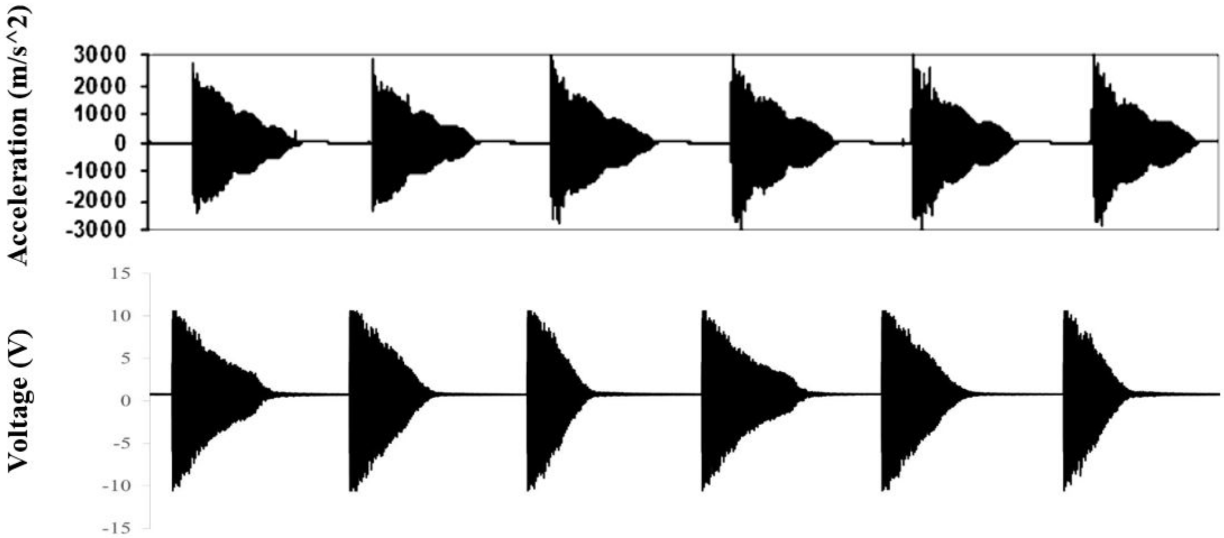

Figure 5: (Top) Riveting hammer vibrational signal as recorded by the laser vibrometer in [6] (Bottom) Riveting hammer vibrational signal as recorded by the piezoelectric/LabVIEW system. Although not shown, both plots share a similar time axis. Each triangular pulse represents a single oscillation of the riveting hammer.

voltage signal can be compared with the acceleration recorded by the laser vibrometer (Fig. 5). As calculated by LabVIEW, the power spectrum describes the energy contribution associated with each frequency in the vibrational signal (Fig 6). ISO 5349 employs a frequency weighting

$$Mag_w = Mag_{uw} \times \left(\frac{16\ Hz}{f}\right) \tag{1}$$

formula (Eq. 1) in which the unweighted magnitude is multiplied by the quotient of 16 Hz and the signal's frequency (Fig. 7).

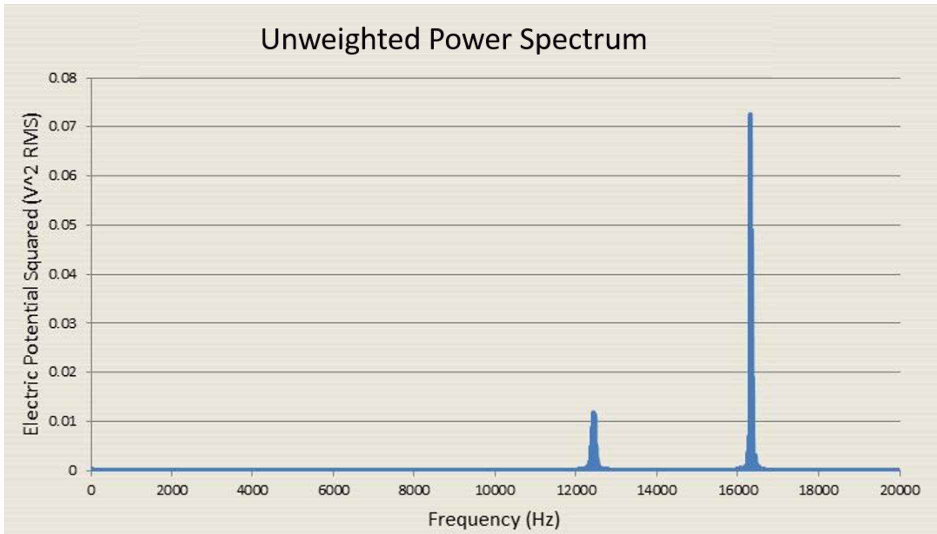

Figure 6: Although 10 frequencies were examined, the two highest at 12.4 and 16.3 kHz contain nearly all of the signal's energy. When the ISO weighting formula is applied the 16.3 kHz signal, its magnitude as well as associated risk is decreased by more than three orders of magnitude.

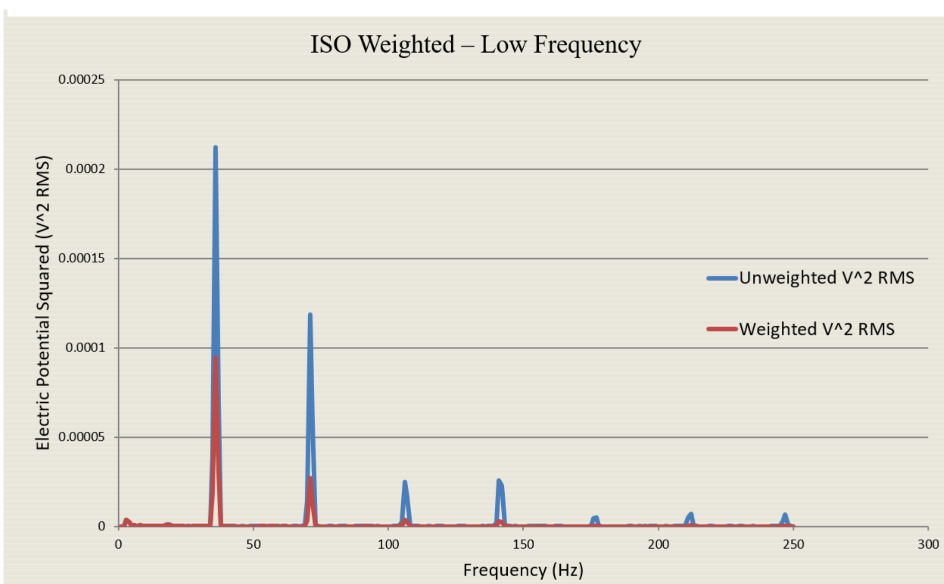

Figure 7: A magnified view detailing the lower frequencies represented in the riveting hammer signal. The y-axis scale in this plot is 320 times smaller than that of Fig. 6.

Several programs were written in the C language to analyze the approximately 135 million collected data points. Ten distinct frequencies were found to contribute nearly all of the signal's vibrational energy (36, 72, 105, 138, 174, 210, 3.9k, 8.4k, 12.4k, and 16.3k Hz). The power spectrum peaks belonging to each of these frequencies were averaged together for each sensor. This resulted in 10 values for each sensor. The quotient of the average dorsal and ventral sensor outputs is called the transmissibility (Eq. 2). Since a substantial difference in output voltage

$$\text{Transmissibility} = \frac{\text{Dorsal Sensor Output}}{\text{Ventral Sensor Output}} \tag{2}$$

(sensitivity) was observed in each sensor, the transmissibility is calculated in reference to the dorsal sensor's baseline reading recorded each day before animal testing began. A transmissibility equal to 1 describes a frequency which is neither attenuated nor amplified after interacting with the rat tail. A frequency with a transmissibility greater than 1 suggests that the rat tail is resonating. Frequencies with a calculated transmissibility less than 1 are believed to represent an absorption of vibrational energy by the rat tail. Absorbed vibrational energy is thought to damage a plethora of biological structures, both macroscopic and microscopic, consequently contributing to the neurodegeneration observed in HAVS.

Table 1: Average power spectrum peaks for the 10 dominant frequencies recorded in the riveting h

Frequency (Hz)	Avg. Trans.
36	7.76
72	1.34
105	1.81
138	3.10
174	4.16
210	18.47
3900	0.57
8400	2.25
12400	0.24
16300	0.19

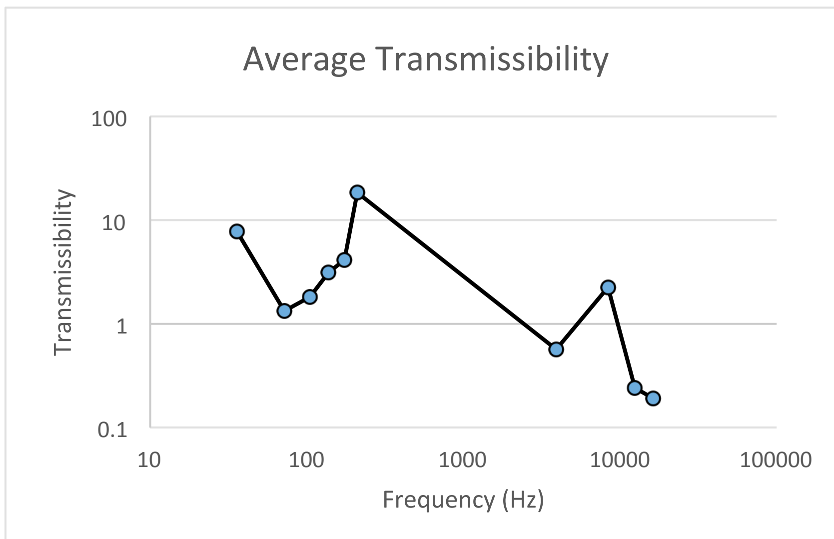

Figure 8: Transmissibility is heavily dependent on the energy associated with each frequency. There is still uncertainty in the field regarding if a large transmissibility and/or a low is to blame for the adverse effects of hand-arm vibration.

ammer vibrational signal.

4. Discussion

The visual similarities between the laser vibrometer and piezoelectric system suggest that piezoelectric sensors are a viable alternative for vibrational analysis in the field of hand-arm vibration (Fig. 5). The piezoelectric system's cost is 1/100 that of the laser vibrometer. Its small size and varying composition (both flexible ceramic and rubber) further encourage the much needed investigation of HAVS both in the workplace and laboratory to readdress ISO 5349.

Findings show that the riveting hammer vibration signal is dominated by two different kHz frequencies, both of which exhibit a transmissibility value less than 0.25 (Fig. 6 and Table 1). It is easy to believe that these large changes in energy are responsible for whatever changes may be observed in nerve populations, but that may not the case. The frequency response of the piezoelectric sensors has not been characterized. This may attribute to the slight differences noted between power spectrums collected by the laser vibrometer and piezoelectric system.[3]

While the initial scope was to examine the effects of recovery over a period of 5 weeks, weekend recovery from Friday to Monday can be analyzed in terms of the vibrational signal. The biodynamic response of the rat tail changes throughout the extended exposure to vibration. Transmissibility describes this response, and recordings from Friday and a following Monday may be compared to show the biological efforts of short term recovery. Perhaps the short recovery promoted by the typical work week causes the cellular repair mechanisms to be susceptible to vibration damage when the work week resumes.

Although initial findings seem promising, no relationships or observations can be made regarding the various nerve populations at this juncture of quantification.

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