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Evaluating the Vibration Exposure of a Power-Assisted Liposuction Device Using a 3D-Printed Finger Adapter

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Abstract: Hand-Arm Vibration Syndrome (HAVS) is a significant occupational health concern, particularly among surgeons who use power tools like power-assisted liposuction (PAL) devices. In this context, this study evaluates the vibration exposure of a commercially available PAL system by using a 3D-printed finger adapter equipped with a affordable tri-axial accelerometer. Measurements were conducted on the handpiece alone and with a cannula attached performed by three operators. Vibration exposure was calculated according to DIN EN ISO 5349-1 standards. Fast Fourier Transform (FFT) analysis confirmed a primary vibration frequency of 75 Hz, consistent with prior research, thus validating the adapter's reliability in capturing the frequency spectrum. The mean overall vibration magnitude (a_{hv}) was $0.54 \pm 0.05 \frac{m}{s^2}$ for the handpiece alone and $2.78 \pm 0.1 \frac{m}{s^2}$ with the cannula attached. The observed precision, indicated by a small standard deviation, suggests the adapter's consistency under controlled conditions. While our measured vibration magnitude was lower than the manufacturer's reported value ($3.77 \frac{m}{s^2}$), this difference likely reflects the manufacturer's testing of larger cannulas. The findings highlight the promise of utilizing a 3D-printed finger adapter, coupled with an low-cost accelerometer, as a accessible and consistent method for quantifying PAL device vibration. Further research is recommended to validate its accuracy across various surgical settings and devices, and to explore its utility in developing effective HAVS mitigation strategies.

Keywords: PAL, vibration, FFT, accelerometer, 3D printed. Python, HAVS, HTV

1 Introduction

Hand-arm vibration syndrome (HAVS) is a significant occupational health concern, characterized by a collection of sensorineural, vascular and musculoskeletal disorders that can arise from prolonged and intensive exposure to hand-transmitted vibration (HTV) [2]. HAVS often manifests as sensations of tingling and/or numbness which are later accompanied by painful, episodic blanching of one or more fingers when exposed to cold, a phenomenon known as "vibration white finger" (VWF) [5]. While the risks of HAVS are well-documented and regulated in many industrial and manual labor sectors, it is often overlooked within the medical field [4]. This oversight is particularly concerning among surgeons who routinely use power tools, including power-assisted liposuction devices (PAL).

The increasing adoption of power-assisted surgical tools underscores the necessity for a thorough evaluation of potential HAVS risks in the medical environment. A key challenge in this evaluation is the accurate measurement of vibration exposure duration. Traditional methods relying on self-reported data tend to overestimate actual exposure times, potentially leading to significant errors in exposure dose calculations [6]. Therefore, developing objective and practical measurement methods is essential. The use of finger- or palm-mounted adapters equipped with tri-axial accelerometers presents a practical approach for measuring vibration on tool handles or handheld workpieces. However, studies indicate that many such adapters can overestimate vibration exposure, especially within the critical middle-frequency range of 16 Hz to 200 Hz [3]. It has also been shown that these measurement errors can be minimized through systematic optimization of the adapter's design and usage.

In this study, we evaluate the vibration exposure of a commercially available PAL device using a finger adapter equipped with an accelerometer in a low-cost and open-source approach.

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2 Materials and methods

2.1 Design and use of finger adapter

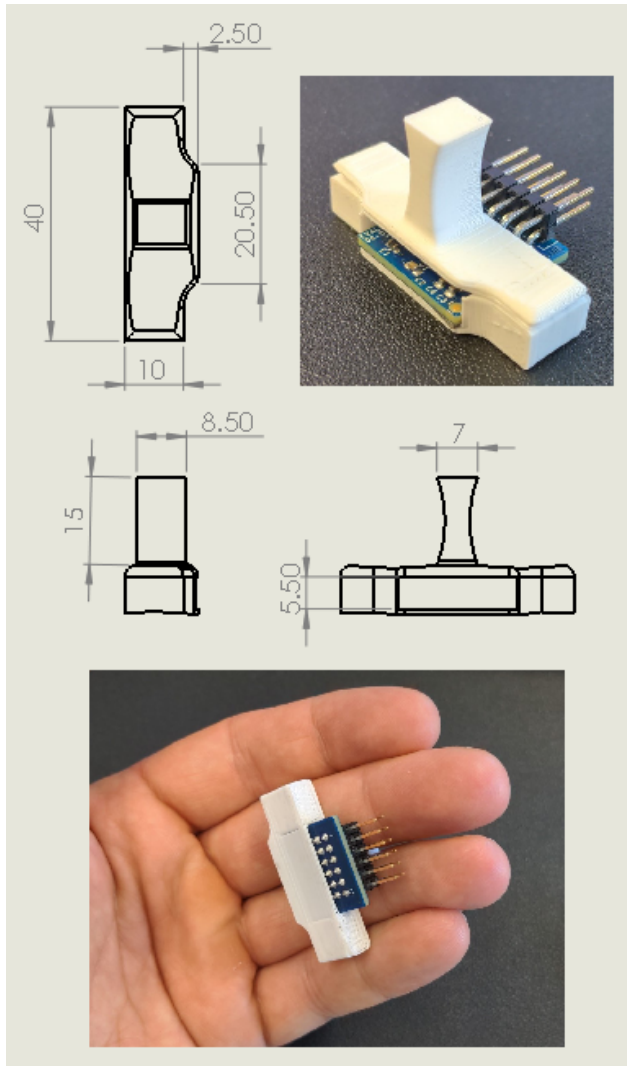


Fig. 1: 3D-printed finger adapter holding an ADXL355 accelerometer.

The accuracy of vibration measurements using finger adapters is influenced by several factors, including the type of tool, adapter model, mounting position and orientation, and individual user characteristics. Studies have identified key causes of measurement inaccuracies when using two-fingered adapters [9]: These include: (1) loss of contact between the adapter and the surface due to insufficient finger grip, especially at frequencies matching the natural resonance of fingers or hand; (2) the extent of contact loss being directly related to the adapter's mass and resulting inertial forces; (3) the tendency of the adapter to rock or tilt on the surface when contact is

lost, particularly during multi-axis vibration exposure; and (4) more pronounced rocking movements with taller adapters.

Drawing upon these identified causes of inaccuracies and the recommendations of Xu et al. [10], we designed our adapter with the following key considerations: (i) minimizing the mass of the finger adapter and accelerometer; (ii) minimizing the adapter's height and ensuring the accelerometer is positioned as close as possible to the contact point; (iii) enabling sufficient finger force to prevent separation during vibration; (iv) ensuring a high natural frequency relative to the fingers; and (v) incorporating damping to reduce resonance effects. It's important to acknowledge that these design goals present inherent trade-offs. For instance, while minimizing mass is crucial, it must be balanced against the need for sufficient stiffness to maintain a high natural frequency and prevent unwanted deformation. Similarly, a lower adapter height reduces rocking, but may compromise the contact area for stable gripping.

Our design carefully navigated these competing factors, prioritizing a configuration that minimizes potential measurement errors while remaining practical for real-world surgical settings. Figure 1 shows the finished adapter fabricated with PLA filament using a FDM printer (Anycubic Kobra Pro). A low-cost tri-axial accelerometer (ADXL355) is firmly attached using an adhesive.

2.2 Experimental Setup

Vibration emissions of a commercially available PAL system (MicroAire-650; MicroAire Surgical Instruments, Charlottesville, VA) were evaluated using a tri-axial accelerometer (ADXL355, Analog Devices, Inc., Wilmington, MA) interfaced with a Teensy 4.1 microcontroller (SparkFun Electronics, Boulder, Colorado). Acceleration data were collected under controlled conditions using a 3D-printed finger adapter and the PAL device operated at full power. Measurements were taken with the PAL handpiece alone and using one type of cannula (300 mm long and 4 mm in diameter). The device was operated at full force.. Testing was conducted with the PAL held in hand using the finger adapter and sufficient contact force so that the adapter does not lose slip or rock. Three different handpiece operators were selected to participate in the data collection, chosen to represent a range of sex and body mass (50 kg female, 70 kg and 90 kg male).

2.3 Data and statistical analysis

To comprehensively assess the potential risk of HAVS, the recorded vibration data were analyzed to determine vibration magnitude and frequency content. As highlighted in recent re-

views of hand-arm vibration studies, the biological effects of vibration are frequency-dependent, with different frequencies potentially affecting different tissues and physiological systems [3]. Analyzing these parameters is crucial for a standardized evaluation of vibration exposure and comparison with established safety guidelines. Therefore, the following steps were performed to process the accelerometer data and calculate relevant vibration metrics, adhering to the guidelines outlined in DIN EN ISO 5349-1 [DIN].

Data from the sensor were analyzed using Python. Raw x-, y- and z-axis acceleration values were outputted including their timestamps and post-processed using the frequency weighing filters defined in DIN EN ISO 5349-1. The standard requires the combined use of a bandpass and frequency weighing filter. The cut-off frequencies of the bandpass filter are at $f_{Wb, highpass} = 6.31$ Hz and $f_{Wb, lowpass} = 1258.9$ Hz. Since we used the native hardware filters of the ADXL355 accelerometer, the bandpass filter slightly deviates from the ISO: $f_{adxl, highpass} = 2.48$ Hz and $f_{adxl, lowpass} = 1000$ Hz. A digital filter equivalent to the standards frequency weighing filter $H_w(s)$ was applied according to [7] and implemented via the SciPy library, yielding weighted acceleration values ($a_{hw x}$, $a_{hw y}$ and $a_{hw z}$). Finally, the data were converted from g to $\frac{m}{s^2}$ and the overall vibration magnitude a_{hv} was calculated by using the weighted root mean square (RMS) acceleration values for each axis according to equation 1.

$$a_{hv} = \sqrt{a_{hw x}^2 + a_{hw y}^2 + a_{hw z}^2} \quad (1)$$

The resulting value represents the frequency-weighted RMS acceleration magnitude in $\frac{m}{s^2}$, providing a standardized measure of vibration exposure. To analyze the frequency content of the vibration, a Fast Fourier Transform (FFT) was performed on the frequency weighted acceleration data using the NumPy library. This allowed for identification of the dominant frequencies present in the vibration signal. All statistical analysis was conducted in Python using the SciPy library. The operator influence was examined as well as the impact of the cannula.

3 Results and Discussion

A total of 18 measurements were recorded for the vibration analysis of the liposuction device, comprising three trials each from three operators, for both the handpiece alone and with the cannula attached. The accelerometer recorded the triaxial acceleration pattern, as illustrated in Figure 2A. Fast fourier transformation (FFT) revealed that the PAL device vibrates at 75 Hz along with several harmonics (multiples of the fundamental frequency) of smaller magnitudes. A representative

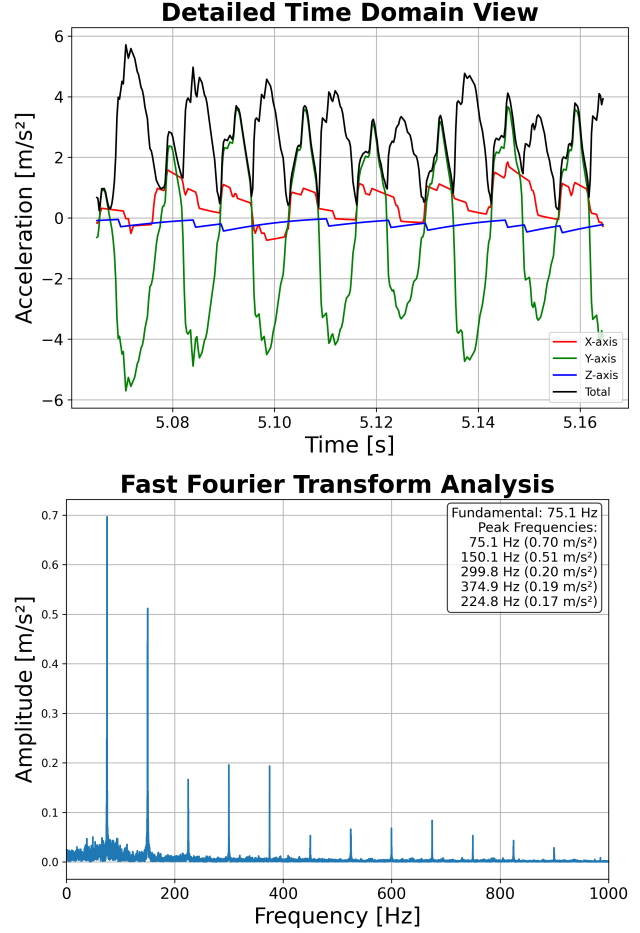


Fig. 2: A representative sample recording generated by the 90 kg male operating the PAL device with the cannula attached. (A) Triaxial vibration pattern in the x, y and z-axes. (B) FFT analysis demonstrates vibration frequencies showing a dominant frequency at 75 Hz along with smaller harmonics in multiples of 75.

FFT analysis can be seen in Figure 2B. This frequency pattern is also found in another study examining the PAL-650 [8] at full power indicating that the developed finger adapter method is reliably capturing the device's fundamental vibration characteristics.

When using the handpiece alone, the mean a_{hv} was $0.54 \pm 0.05 \frac{m}{s^2}$ and with the cannula attached $2.78 \pm 0.1 \frac{m}{s^2}$. The manufacturer's manual states a tested vibration exposure of $3.77 \frac{m}{s^2}$. Considering that larger and bent cannulas are available for the PAL-650, our result of $2.78 \frac{m}{s^2}$ (cannula attached) seems plausible, as the manufacturer's reported value likely reflects a worst-case scenario using these cannulas, which would alter the mass and center of gravity, potentially leading to higher vibration magnitudes.

Statistical analysis was performed to evaluate the influence of different operators and cannula conditions on handpiece acceleration. A one-way ANOVA revealed no signifi-

cant differences between the three operators ($F = 0.0183$, $p = 0.9819$), indicating consistent performance across different users. Without cannula, mean acceleration values were similar for Person A ($0.51 \pm 0.03 \frac{m}{s^2}$), Person B ($0.56 \pm 0.07 \frac{m}{s^2}$), and Person C ($0.55 \pm 0.02 \frac{m}{s^2}$). With the cannula attached, operators also exhibit consistent performance with mean values for Person A ($2.66 \pm 0.02 \frac{m}{s^2}$), Person B ($2.88 \pm 0.05 \frac{m}{s^2}$), and Person C ($2.78 \pm 0.06 \frac{m}{s^2}$).

A paired samples t-test was conducted to compare acceleration values between no-cannula and cannula conditions on the same handpiece. The test revealed a significant difference between the two conditions ($t = -61.98$, $p < 0.0001$). The mean acceleration without cannula ($0.54 \pm 0.05 \frac{m}{s^2}$) was substantially lower than with the cannula attached ($2.78 \pm 0.10 \frac{m}{s^2}$). This represents approximately a five-fold increase in acceleration when the cannula is attached.

The small standard deviations observed in our measurements ($0.05 \frac{m}{s^2}$ for the handpiece alone and $0.1 \frac{m}{s^2}$ with the cannula attached) suggest that the finger adapter provides relatively precise and repeatable measurements under the controlled conditions of our study. However, it is important to note that a small standard deviation does not guarantee accuracy, and systematic errors may still be present. Further research is needed to determine the absolute accuracy of the adapter and its reliability across a wider range of conditions. Nevertheless, the observed precision supports the use of the finger adapter for comparing vibration exposure under different test setups within this study.

4 Conclusion

In this study, we demonstrate the use of a low-cost accelerometer with a 3D printed finger adapter as a convenient method for evaluating the vibration exposure of a PAL device. Our findings revealed a fundamental vibration frequency of 75 Hz and mean vibration magnitudes of $0.54 \frac{m}{s^2}$ for the handpiece alone and $2.78 \frac{m}{s^2}$ with a cannula. These results align with previous research and support the potential of our method for practical and consistent vibration measurement.

However, this study was conducted under controlled conditions with a specific PAL device and one cannula type. Further research is needed to assess the accuracy and reliability of the finger adapter across diverse surgical settings and devices. Future studies should also explore the impact of different cannula types and on-the-job trials on vibration exposure. Despite these limitations, our study highlights the accessibility of assessing vibration exposure in surgical settings by using a low-cost sensor and a 3D printed finger adapter.

Author Statement

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