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Focal Vibration Therapy: Vibration Parameters of Effective Wearable Devices

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Abstract: Focal vibration therapy can provide neurophysiological benefits. Unfortunately, standardized protocols are non-existent. Previous research presents a wide range of protocols with a wide range of effectiveness. This paper is part of a broader effort to identify effective, standardized protocols for focal vibration therapy. The vibration characteristics of four commercially available focal vibration devices that have been used for research and clinically were measured. An accelerometer was used for the measurements. Frequency and peak-to-peak amplitude were measured. Measurements were made when the devices were free and then again when they were strapped to the human body. Vibration frequency ranged from 120 to 225 Hz. Free vibration amplitude ranged from 2.0 to 7.9 *g*'s (peak-to-peak). When the devices were strapped to the body (constrained), vibration amplitude decreased by up to 65.7%. These results identify effective ranges of focal vibration frequency and amplitude. They illustrate the importance of identifying vibration environment, free or constrained, when quoting vibration characteristics. Finally, the inconsistency of multi-actuator devices is discussed. These results will guide protocol development for focal vibration and potentially better focal vibration devices.

Keywords: focal vibration therapy, vibration frequency, vibration amplitude, vibration intensity

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1. Introduction

Vibration therapy devices can take one of two forms: whole body vibration (WBV) or focal vibration (FV). In WBV, vibration is delivered to the body through a relatively large vibration platform upon which a patient can sit or stand. In FV, vibration is delivered through a relatively small vibrating mechanism applied to specific muscles and/or tendons.

The neurophysiological benefits of vibration have been of interest for over a century. The earliest examples of WBV and FV devices were developed by Gustav Zander [1], John Kellogg [2], and Joseph Granville [3]. Since then, vibration, especially WBV, has been shown to be beneficial for a number of conditions. For example, vibration has been used in counteracting loss of muscle mass [4], in reducing bone mineral density decline [5], in improving balance and mobility [6], and in treating chronic lower back pain [7]. While WBV has traditionally been more popular, FV is now being studied more closely, primarily because of the potentially harmful effects of WBV [8, 9].

There is a lack of standardized application protocols for WBV [10]. The situation is similar for FV. Different studies have used various vibration frequencies, amplitudes/intensities, and dosages. For example, FV has been used with vibration frequencies in the range of 80 Hz [11] to 300 Hz [12] for upper limb post stroke recovery. Similarly, vibration displacement has ranged from as low as 0.2 to 0.5 mm [13], up to 2 mm [12]. For both WBV and FV, different studies have demonstrated varied degrees of success. Therefore, an effective vibration therapy protocol is still undefined. We will address this knowledge gap in this paper, focusing on FV protocols, as FV has been studied less extensively. However, our findings and approach can also be used to quantify WBV and help establish effective WBV therapy protocols.

Drawing from proven FV approaches, we focused on devices available in the US, and those that are wearable or very portable, i.e., hand-held. This is the first step in identifying an effective FV protocol. Future work would involve extensively testing these approaches and their variations with human subjects. In the present study, we measured the vibration characteristics of commercially available FV devices that have been known to be effective. These devices have been consistently used for therapy in the past with a sizable number and variety of users, as compared with experimental devices, which are usually evaluated for a limited number of times on a limited number of patients.

To the best of our knowledge, this is the first work that rigorously evaluates current commercially available FV devices in the US. The closest related works that do this are our earlier research [14]. In our earlier research, we tested a subset of the available modes for commercially available FV devices. While the results were interesting and provided insightful information, they were somewhat limited and difficult to interpret. The work by Botter et al. provided a detailed evaluation [15]. However, they used devices that are not available for use in the US. In addition, they evaluated bulky pressure-based devices, while we focus on more portable FV devices.

2. Materials and Methods

Vibration characteristics were measured for the four different commercially available devices. They are described in Section 2.13. The devices and modes are listed in Table 1.

Table 1: List of devices and modes used. Not all specifications have been provided by the manufacturers. Novafon frequency data [16] and Myovolt frequency data [17] are from their respective websites.

Device	Mode	Vibration pattern	Manufacturer specs.	Wearable
Vibracool	n/a	constant	-	Yes
Novafon	Mode I at max. intensity	constant	120 Hz	No
	Mode II at max. intensity	constant	60 Hz	
	Mode I at min. intensity	constant	120 Hz	
	Mode II at min. intensity	constant	60 Hz	
Myovolt 3 actuator	Mode 1	sinusoidal	-	Yes
	Mode 2	pulsing on/off	-	
	Mode 3	constant	120 Hz	
Myovolt 2 actuator	Mode 1	sinusoidal	-	Yes
	Mode 2	pulsing on/off	-	
	Mode 3	constant	120 Hz	

2.1. Devices Tested

Four commercially available focal vibration devices were tested: Vibracool [18], Novafon Pro [16], and two Myovolt [17] series of devices (Fig. 1). The Vibracool device (Fig. 1a) is marketed as a focal vibration device for pain relief. It is a battery-powered device with a single vibration motor that delivers a constant vibration. To wear the device, different styles of pouches with straps are available. Hot packs and cold packs are also available to use together with the device [18].

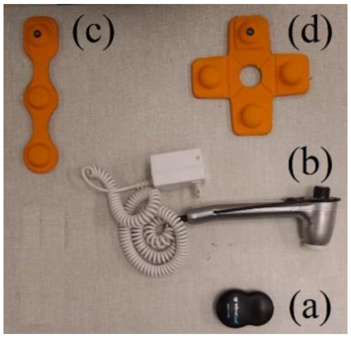

Figure 1. Focal vibration (FV) devices that are the subject of this paper: (a) Vibracool, (b) Novafon Pro, (c) Myovolt two-actuator, and (d) Myovolt three-actuator.

The Novafon Pro device (Fig. 1b) is marketed as a general health massager. It provides focal vibration by use of a transducer, where the vibration head is directly connected to the transducer. The device is powered by mains electricity. It is advertised to have two modes: Mode I (120 Hz) and Mode II (60 Hz). The modes can be selected using a rocker switch. For each mode, intensity can be controlled by a rotating knob [16].

Myovolt devices (Fig. 1c, Fig. 1d) are marketed as wearable muscle relief devices, primarily for athletes. They are battery-powered. There are two models: three-actuator and two-actuator. The three-actuator models have three vibration motors and the two-actuator models have two vibration motors, embedded together into a single flexible structure. Various straps are available for attaching them on different body parts. The Myovolt devices operate in three different modes: 1) sinusoidal, with intensity changing sinusoidally; 2) pulsing, alternating between on and off; and 3) constant vibration. The modes can be changed by pressing a mode button [17].

Those four devices were selected for testing due to their commercial availability and use for research and clinical practice. Vibracool is commercially available. It has been used in FV therapy, and has been proven to provide pain relief [19]. In fact, it has been demonstrated to be better than TENS [20]. Novafon Pro is commercially available, and has been used by therapists for FV therapy. It has proven to be effective [21, 22]. There are many other devices similar to Novafon Pro, but not shown, that have been used for research or clinical practice. Finally, Myovolt devices are also commercially available and have been used in research studies [23-26].

2.2. Overall Approach

Each device was tested under free vibration and constrained vibration conditions. For free vibration, the device was held in the hand lightly, with the forearm resting on a horizontal support (see Fig. 2). For constrained vibration, each device was placed on the forearm. The forearm was kept horizontal and the device was applied from above (see Fig. 3). Consistent pressure was maintained through the placement of a weighted securing strap. The strap was loosely placed around the device and a 500-g mass was suspended from the strap from below. This pressure seemed to be

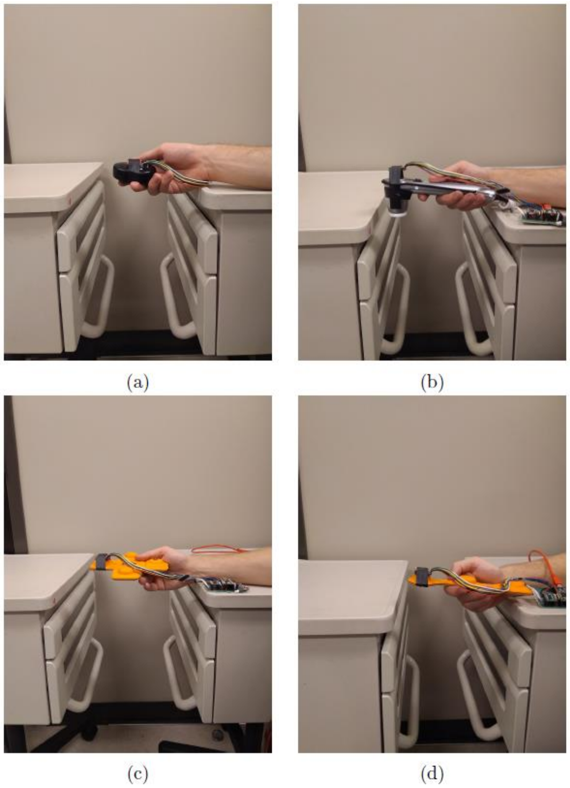

Figure 2. Test setup for free vibration. The vibration device was held lightly in the hand. (a) Vibracool, (b) Novafon Pro, (c) Myovolt three-actuator, and (d) Myovolt two-actuator.

comfortable, yet strong enough to hold the device in place and firmly apply vibration. A 50-g mass was used for the Novafon to avoid dampening out the vibration. This was based on the 28 to 57 g (1 to 2 oz) range recommended by [27].

For measuring vibration characteristics, a distinction was made between the single-actuator devices (Vibracool, Novafon Pro) and multi-actuator devices (Myvolt two-actuator and three-actuator) due to their vibration characteristics. This was because the multi-actuator devices had time-varying vibration characteristics. This was observed in all three modes (sinusoidal, pulsing, and constant vibration).

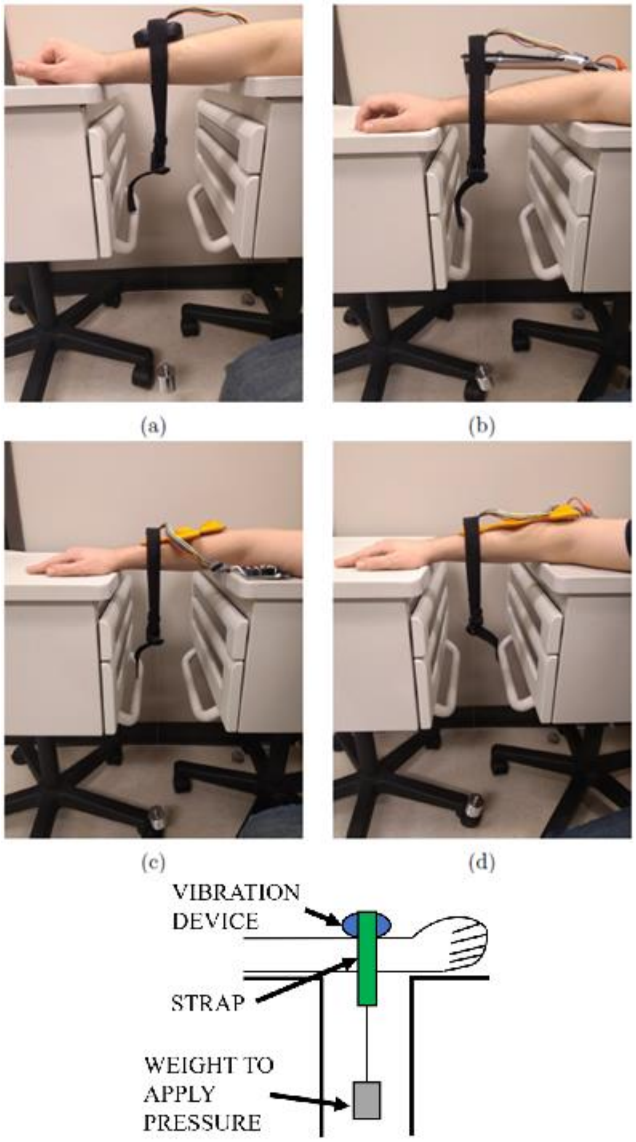

Figure 3. Test setup for constrained vibration using a strap and weight to secure the device, and a weight to apply the vibration with a constant pressure. (a) Vibracool, (b) Novafon Pro, (c) Myovolt three-actuator, (d) Myovolt two-actuator, and (e) representative constrained vibration.

2.3. Single-Actuator Devices

For the two single-actuator devices (Vibracool and Novafon Pro), an accelerometer (STMicroelectronics LSM9DS1, ±16 *g*'s full scale, 952 Hz sampling rate) was used to measure acceleration along the axis of vibration. A microcontroller (PJRC Teensy 3.2, 96 MHz) was used to read the raw accelerometer data and transfer it over USB to a computer to derive the measurement parameters. For each device, the accelerometer board was taped on to the body of the device. Peak-to-peak acceleration intensity (g's) and frequency (Hz) were measured. Peak-to-peak acceleration intensity was computed by taking the difference between mean peak and mean valley (negative peak) over 200 samples (0.21 s, @ 952 Hz sampling rate). Frequency

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was computed by using mean zero-crossing rate over the same 200 samples. This measurement process was repeated three times, for each mode, for each device.

For the Novafon Pro, both Mode I and Mode II were used (120 Hz and 60 Hz). For each mode of the Novafon Pro, the minimum and maximum intensity was used. The tested modes are listed in Table 1.

2.4. Multi-Actuator Devices

The process of measuring the vibration characteristics of the two multi-actuator devices (Myovolt two-actuator and three-actuator) was different from Section 2.3, since the frequency and intensity were changing over time. The same accelerometer as in Section 2.3 was used (STMicroelectronics LSM9DS1, ±16 g's full scale, 952 Hz sampling rate). The accelerometer board was taped on to the body of the device, and acceleration was measured along the axis of vibration. In contrast to the previous approach for single-actuator devices, accelerometer data were recorded over 9520 samples (10.00 s, @ 952 Hz sampling rate). Since a constant peak-to-peak acceleration could not be measured, the maximum peak-to-peak acceleration was computed by using 95th and 5th percentiles of the peaks and valleys (negative peaks) as follows:

$$(pk - pk)_{max} = P_{95})_{peaks} - P_{5})_{valleys} \tag{1}$$

For both multi-actuator devices, intensity was computed for all three modes, i.e., Mode 1 (sinusoidal), Mode 2 (pulsing on/off), and Mode 3 (constant).

The vibration frequency was not measured because it changed over time and the multibody vibration dynamics distorted the frequency even further. This made frequency estimation using ZCR relatively unreliable.

Additionally, the time period for the vibration pattern for Mode 1 (sinusoidal) and Mode 2 (pulsing on/off) patterns was computed. Note that this is not related to frequency of vibration, which was not measured because it changed over time. The vibration pattern time period was computed by filtering the peaks through a 9-point moving average, then using a zero-crossing rate with a suitable threshold. Since Mode 3 did not have a vibration pattern, no pattern frequency was computed. Vibration pattern measurements were repeated three times for each mode for each device. An average was computed using the three free vibration and three constrained vibration samples, where the average was based on data from the six tests.

2.5. Relating Vibration Amplitude and Acceleration

Typically, past works have quoted vibration intensity in terms of displacement (or vibration amplitude). It is not clear why this has been a trend, since acceleration is relatively easier to measure, especially in the constrained vibration case. Perhaps this has been a trend because vibration systems and accelerometers have been miniaturized to feasible costs and sizes in only the past two decades. Vibration technology itself has been around for much longer, i.e., well over a century. In the past, bulkier and more expensive technologies, e.g., high speed cameras and linear variable differential transformers (LVDT), were the most feasible options. These technologies can directly measure displacement (or vibration amplitude), possibly explaining why vibration intensity has been widely reported in the literature. We believe that using acceleration as a metric for vibration delivered is more logical and economical, given the widespread availability of low-cost MEMS accelerometers.

In the spirit of making the comparison with vibration displacement (or amplitude) easier, we present a conversion between displacement (or vibration amplitude) and peak-to-peak acceleration. Assuming a sinusoidal vibration pattern with angular frequency ω rad/s and amplitude $A/2$ m (peak-to-peak amplitude A), the displacement s from the mean position is defined by:

$$s = \frac{A}{2}\sin\,(\omega t) \tag{2}$$

Alternatively, ω can also be defined in terms of frequency f in Hz:

$$s = \frac{A}{2}\sin\,(2\pi f t) \tag{3}$$

Velocity is the first derivative of displacement:

$$\frac{ds}{dt} = A\pi f cos\,(2\pi f t) \tag{4}$$

Acceleration is the second derivative of displacement:

$$\frac{d^2 s}{dt^2} = -2A\pi^2 f^2 \sin\,(2\pi f t) \tag{5}$$

The displacement s is maximum when $ds/dt = 0$. Thus, from (4),

$$\cos(2\pi f t) = 0 \tag{6}$$

$$2\pi f t = \frac{\pi}{2}, or\,\frac{3\pi}{2}, or\,\frac{5\pi}{2}, \ldots \tag{7}$$

We also know that when displacement is maximum, the acceleration is maximum (in the opposite direction). Taking the first value $\pi/2$, we get the maximum acceleration from (5):

$$acceleration_{Max} = -2A\pi^2 f^2 sin\,(\frac{\pi}{2}) \tag{8}$$

Rearranging, we have a relation where we can compute peak-to-peak amplitude A (m) given maximum acceleration (ms^{-2}) and vibration frequency f (Hz):

$$A = -\frac{acceleration_{Max}}{2\pi^2 f^2} \tag{9}$$

If acceleration is instead in g's, and 1g is 9.81 ms^{-2}, then the peak-to-peak amplitude A (m) is given by:

$$\mathrm{A} = -\frac{4.905 acceleration_{Max}}{\pi^2 f^2} \tag{10}$$

Maximum acceleration is half of peak-to-peak acceleration. Vibration amplitudes are typically on the order of mm. In terms of peak-to-peak acceleration in g's, the peak-to-peak amplitude A (mm) is given by:

$$A = \frac{2452.5 acceleration_{PKPK}}{\pi^2 f^2} \tag{11}$$

Therefore, to convert between peak-to-peak vibration amplitude (mm) and peak-to-peak vibration acceleration (g's), (11) may be used, if the frequency of vibration (Hz) is known.

3. Results

3.1. Vibration Frequency and Intensity

The vibration frequency and intensity that were measured for each of the four devices in the free vibration condition are summarized in Fig. 4. For the constrained vibration condition, the relative change in vibration frequency and intensity is shown in Fig. 5. Vibration intensity is defined by peak-peak acceleration, unless otherwise specified.

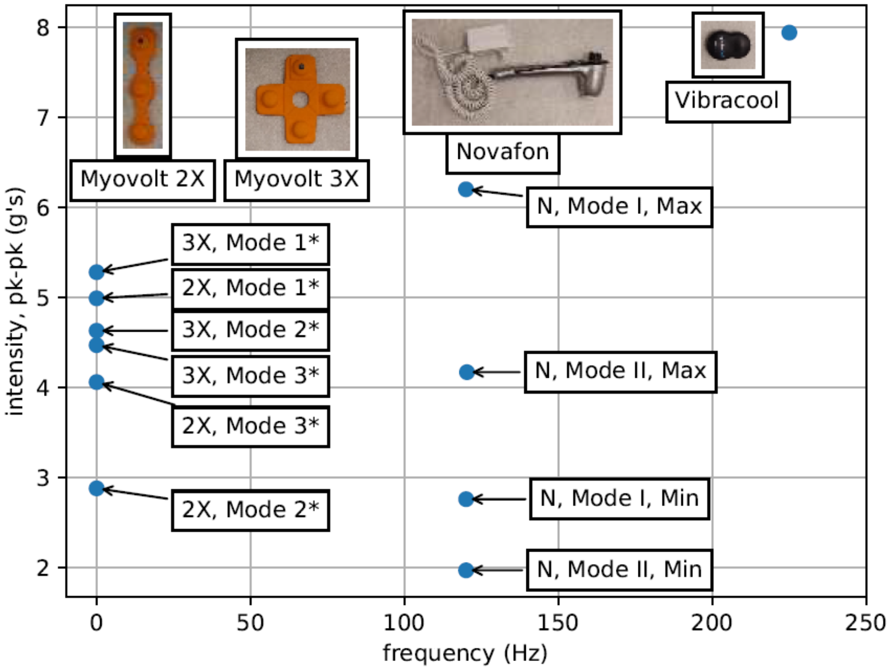

Figure 4. Frequency and peak-to-peak intensity vibration measured for the four FV devices in the free vibration setup. "*" indicates that the maximum peak-peak intensity was measured, and that vibration frequency was not measured.

Considering vibration frequency in the free vibration case (Fig. 4), the Vibracool device ran at a higher frequency of 225 Hz than did the Novafon (about 120 Hz). The Novafon Mode II was not 60 Hz, as claimed by the manufacturer [16]. From these data, we can deduce that the free vibration frequency is in the range of 120 to 225 Hz.

In terms of vibration intensity in the free vibration case, the Vibracool device had the highest intensity of about 7.9 g's. The Myovolt devices were generally clustered around 4.1 to 5.3 g's, with the exception of the Myovolt two-actuator in Mode 2, which was at 2.9 g's. Compared with this cluster, the Novafon device intensity was higher (Mode I, maximum), comparable (Mode II, maximum), or lower (Mode I, minimum; Mode II, minimum). From these data, we can deduce that the vibration intensity of these devices ranges from 2.0 to 7.9 g's.

With reference to vibration frequency in the constrained vibration case (Fig. 5), it decreased slightly for the Vibracool device (4.7%), and dropped significantly (31.1%) for the Novafon device for one of its four modes (Mode II, maximum). Frequency remained consistent for the other three modes of the Novafon device. As previously mentioned, frequency was not measured for the Myovolt devices.

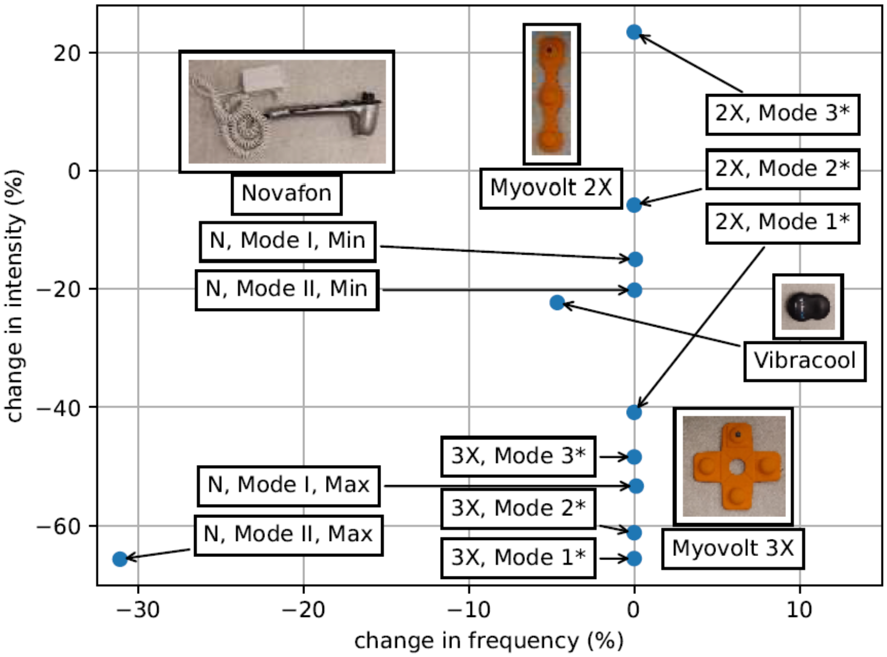

Figure 5. Change in frequency and peak-to-peak intensity measured for the four FV devices for the constrained vibration setup. The change shown is relative to the free vibration case. Negative numbers indicate a decrease. "*" indicates that the maximum peak-peak intensity was measured, and frequency was not measured.

Observing the change in vibration intensity in the context of the original vibration provides a different perspective on the tests (Fig. 6). Without considering the identity of each device, it is apparent that the vibration intensity for an FV device generally decreases once it is applied to the body. Furthermore, the greater the free vibration intensity of a device, the greater the percentage decrease in intensity when it is applied to the body.

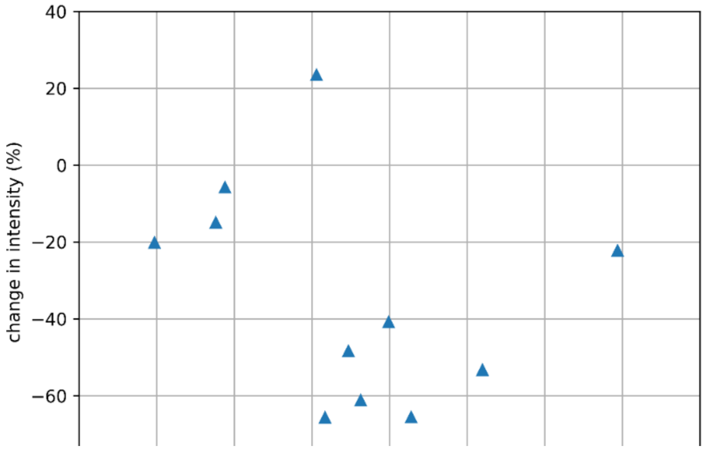

Figure 6. Change in vibration intensity from the free vibration to the constrained vibration setup. The y-axis shows the intensity for the free vibration setup. The x-axis shows the change in intensity between the two setups, relative to the free vibration setup. A negative number indicates a decrease.

3.2. Vibration Pattern

For both Myovolt devices, the pulsing pattern period was approximately 4.2 s for Mode 1 (sinusoidal) and 1.05 s for Mode 2 (pulsing on/off). The results are summarized in Table 2. For Mode 1 (sinusoidal), vibration was on for 2.1 s (ramp up, peak, ramp down) and then off for 2.1 s. Similarly, for Mode 3 (pulsing on/off), the vibration was on for about 0.52 s and then off for about 0.52 s. The Myovolt multi-actuator devices had time-varying vibration characteristics. This was observed not just in the sinusoidal and pulsing modes, but also in the constant vibration mode (see Fig. 7).

Table 2. Period of vibration pattern. "*" indicates an average from 2 tests instead of 6.

Device	Period (s)
Myovolt 3 actuator (Mode 1)	4.21
Myovolt 3 actuator (Mode 2)	1.05
Myovolt 2 actuator (Mode 1)	4.19
Myovolt 2 actuator (Mode 2)	1.05*

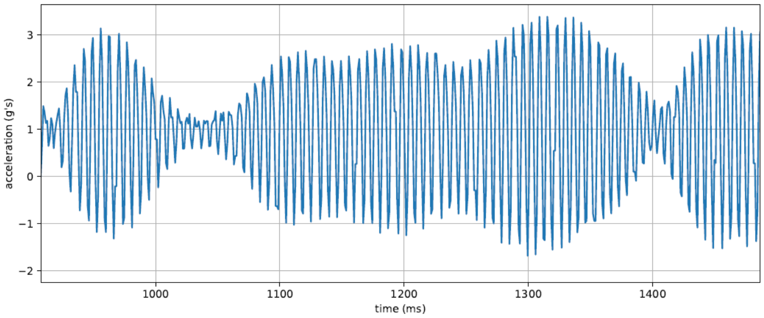

Figure 7. Example of variation in vibration characteristics of the Myovolt multi-actuator vibration devices. These data are from a Myovolt two-actuator in Mode 3 (constant vibration) in the constrained setup. Plot shows the raw accelerometer data along the axis of vibration. Ideally, the peak-to-peak distance should remain constant.

3.3. Relating Vibration Amplitude and Acceleration

Equation (11) is illustrated in Fig. 8 for a range of 1 to 10 g's peak-to-peak intensity, for some representative frequencies.

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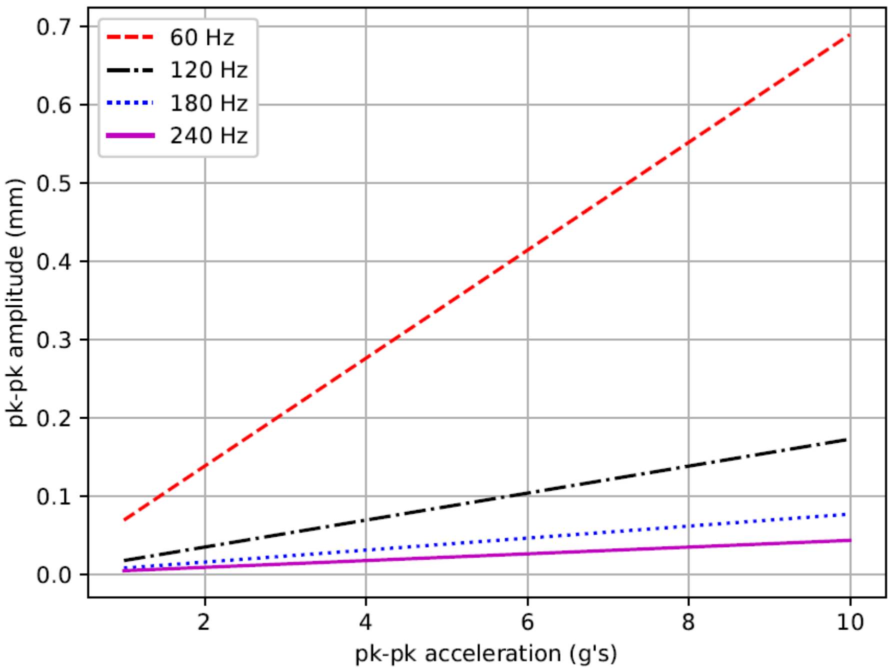

Figure 8. The relationship between peak-to-peak vibration amplitude (*mm*) and peak-to-peak vibration intensity (*g*'s) at frequencies of 60, 120, 180, and 240 Hz. The general relationship is summarized in Equation (11).

4. Discussion

Little is known about the effective vibration characteristics of FV devices. In this study, we measured vibration characteristics of four commercially available FV devices. Anecdotal and literature evidence exists indicating that these devices can be effective, but the application of the FV therapy was limited. One factor influencing limited use is the lack of clinical practice guidelines for FV therapy. Much is unknown regarding how much vibration was actually delivered to the target muscles or body segments, as little research on the exact delivery of FV exists. Since the vibration characteristics of FV devices can be used as a starting point to devise FV therapy protocols, we conducted the experiments in this study to quantify the vibration delivery of four commercially available devices that have been used in clinical settings.

We measured peak-to-peak acceleration and vibration frequency. In the case where the devices were free to vibrate, peak-to-peak acceleration ranged from about 2.0 to 7.9 *g*'s. The vibration frequency ranged from about 120 to 225 Hz. When the devices were worn on the body, in general, the peak-to-peak vibration intensity dropped by 5.8% to 65.7%. This indicates that when quoting FV parameters, it is necessary to specify the vibration condition (free-vibration or constrained-vibration). The constrained-vibration condition is not an accurate representation of the vibration delivered to the body. The frequency drop in the Novafon vibration device can likely be attributed to the fact that the transducer is in direct contact with the body, and so the vibration mechanism and hence the driving (excitation) frequency can be physically hindered. This is different from typical vibration motor-based devices, where the vibration mechanism is enclosed and the driving or excitation frequency cannot be physically hindered. From these data, it is apparent that, in general, vibration frequency does not change significantly when applied to the body.

Vibration intensity in the constrained vibration case (Fig. 5) is the most interesting because it reflects a realistic scenario where the FV device is applied to the body. Three clusters of changes occurred in intensity. First, there was a significant decrease ranging from 40.9% (Myovolt three-actuator, Mode 3) to 65.7% (Novafon Mode II, maximum). Next was the cluster of moderate decrease in intensity ranging from 5.8% (Myovolt two-actuator, Mode 2) to 22.3% (Vibracool). The third cluster with a lone data point showed a moderate increase in vibration intensity to 23.5% (Myovolt two-actuator, Mode 3). We can deduce that when worn on the body, the vibration intensity of a device can decrease anywhere from 5.8% to 65.7%. For the Myovolt two-actuator device, the increase in intensity can be attributed to the second vibration motor, which could have been vibrating in phase to amplify the vibration, i.e., constructive interference. Alternatively, this could be attributed to the structural dynamics of the Myovolt two-actuator device. For example, the resonant frequency in the constrained configuration may have been closer to the vibration motor frequency, resulting in higher vibration intensity. Thus, in free vibration, some vibration energy may have been lost in vibrating the flexible structure, while in constrained vibration, less vibration energy would have been lost.

The Myovolt device provides different vibration patterns. This could provide an alternative starting point for FV therapy. Time-variant vibration patterns such as these may be more effective than constant vibration due to human mechanosensitive neurons becoming more desensitized in response to sustained mechanical stimulation [20]. Therefore, to maximize response to the vibration, applying vibration that changes over time might be more appropriate.

Lastly, we derived the relation between vibration amplitude and acceleration force. For clinicians, it could be easier to use the displacement (amplitude) to describe the vibration intensity, which is why in most of the literature, the vibration amplitudes were reported as displacement in mm. However, it is critical to know how much acceleration force was applied with each given displacement. As mentioned above, the relationship between the amplitude and acceleration was also dependent on frequency. As shown in Fig. 8, the lower the frequency, the higher the peak-to-peak amplitude for a given peak-to-peak acceleration.

The current study had some limitations. First, we only included four commercially available wearable FV devices in this study. We selected the devices based on their applications in clinical settings. In the future, we will include more devices based on different features and designs. We will also try to include the non-portable devices that have been tested in another study to compare the performance difference among them [15]. Second, the accelerometer used in the present study was not optimized. We will test more FV devices with an accelerometer with a higher sampling rate to improve the accuracy of our results. Finally, all of the FV devices were applied to the same person (one of the researchers) on the same muscle. In future study, we will test more FV devices on different muscles and tendons and will test the devices on more individuals to determine whether the FV parameters change with body types, e.g., another variable in FV therapy that must be addressed. In future, we will also work towards developing a more unambiguous metric for quantifying the amount of vibration delivered. Using only amplitude and frequency, or acceleration and frequency, might not be sufficient.

5. Conclusion

The main contributions of this paper are twofold. First, the findings will help researchers and clinicians to learn the real vibration delivered by different techniques, especially when applied to the human body. Second, the results can be used to guide the future application and design of new FV technology that can deliver precise vibration for rehabilitation. We tested, analyzed, and compared the vibration frequencies and intensities of four different wearable FV devices at free hand and that are used to deliver therapeutic vibration to the human body. We highlighted that having devices with multiple vibration sources in the same structure can result in inconsistent FV dosage. We present a conversion chart to convert between vibration amplitude and acceleration. Going forward, the authors feel that the task of better quantifying the vibration delivered is crucial to developing repeatable FV therapy protocols. Finally, the quantification approaches developed in this study can also be used to quantify WBV therapy delivery, which can guide WBV clinical practice.

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