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Developing a new focal vibration and heat therapy system

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Abstract: Vibrational heating therapy is a type of physical therapy that uses the application of heat and vibrations to stimulate the body's healing process. The therapy is believed to promote circulation, reduce inflammation, and relieve muscle tension. It is often used to treat conditions such as arthritis, fibromyalgia, and sports injuries. This paper presents the design-decisions for a device treating muscle soreness and to increase muscle strength through a combination of heat and vibration therapy to the upper leg. The system comprises far-infrared heat elements for heat transfer and two types of eccentric rotating masses (ERMs) and a linear resonant actuator (LRA) to vibrate muscle tissue. It discusses heating and vibration capability and performance. To optimize the mechanical effects of vibration therapy, the device must excite the muscle with an acceleration of more than 2 g and with a bandwidth as wide as the range of the muscle natural frequencies. For testing the heating and vibrational systems, they were tested in the same device on six different subjects with ethics permission from Technical University of Hamburg to obtain accurate results. Both ERMs were driven by DC power and yielded a bandwidth of about 30 Hz with a linear progression of acceleration over frequency, while the LRA was driven by AC power and achieved a bandwidth of about 24 Hz in the form of a bell curve. Also the selected heating element provides the desired temperature between 40 °C to 50 °C. Overall, the initial technical study showed promising measurement results and a mechanical effect in using this combination of heat and vibration therapy. As an outlook, the technical design of the next version of the device will include multiple actuators around the leg to provide more acceleration and aims to combine multiple LRAs with slightly shifted natural frequencies into one actuator module to extend the bandwidth.

Keywords: Heat therapy, vibration therapy, muscle soreness, eigenfrequency

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1 Introduction

According to Statista [1], only 14.27 million people in Germany exercise several times a week. While there is currently no way to completely replace a physical workout, there are some ways to support it and help with recovery afterwards. The use of vibratory stimuli has shown practical applications in the areas of therapeutic rehabilitation and exercise performance [2] and is referred to as vibration therapy (VT). VT devices generally come in two forms: Whole Body Vibration (WBV), in which the person stands on some sort of platform, and Focal Vibration (FV), in which only a specific area or muscle is stimulated. Interest in the physical benefits of vibration has increased in recent years. While results have been beneficial in preventing loss of muscle mass, reducing bone mineral density decline (both common in age), and aiding recovery from delayed-onset muscle soreness (DOMS), there are also some studies that find no benefit [3]. In general, VT has two adjustable parameters: Vibration frequency [Hz] and displacement (measured in either amplitude [mm] or acceleration [g]), and the exact ratio greatly affects the outcome [3].
A commonly used range for heat therapy [4] is usually in the range of 40-50 °C and comes in a variety of forms, all of which warm the body over a longer period of time. Its benefits range from muscle relaxation and pain relief to aid in recovery. The main disadvantage is that too much heat should be generated, which can be avoided with careful use.
While there are some portable devices for FV such as the Myovolt [5] and even one with an additional heat therapy in Hyperice [6], they all have a specific frequency. Some have different patterns such as wave, pulse or constant, but there are no option to set a specific configuration. [7] shows that a muscle shows maximum muscle activity in accordance with the mechanical resonance of itself, which changes according to muscle contraction. Therefore, an optimal use of FV would be to actuate the muscle at a multiple of its natural frequency.
The goal of this work is to develop such a device with low weight (less than 700 grams), capable of generating acceleration greater than 8 g, frequency in the range of 20 to 170 Hz, and temperature up to 50 °C.

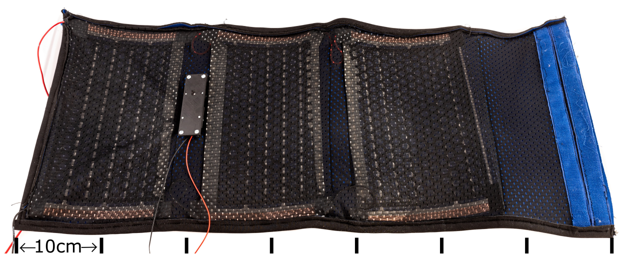

Fig. 1: Assembly prototype 1: The device is powered by an external power supply of up to 24 V or 20 W.

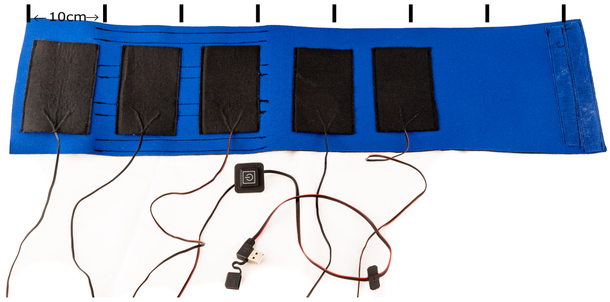

Fig. 2: Assembly prototype 2: The device is powered by a USB port.

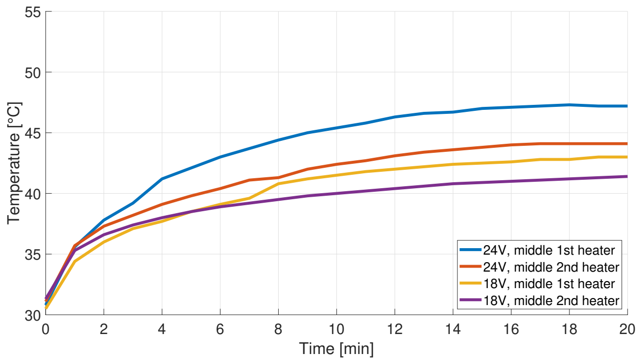

Fig. 3: Prototype 1: 18 V and 24 V comparison of 1st and 2nd heating element

2 System design

The two main components for the product design is the choice of actuators and heat source. The following section gives an overview on the decision-making-process.

A total of 11 different Actuators are evaluated and scored in the criteria of cost, frequency, amplitude, size, and operating range. From this evaluation, two ERMs are chosen for further validation of the system with their results shown in Section 3.2.

A total of 6 different commercially available heating systems were evaluated and rated based on cost per cm^2, ease of control, heat distribution, speed to reach initial temperature, and temperature range. From this evaluation, two far-infrared systems are chosen to be purchased for the system validation with their results shown in Section 3.1.

2.1 Assembly

To attach the heating system and actuator to the body, a compression wrap is made of flexible neoprene and tightened with Velcro. The heating systems are sewn onto two separate wraps, with the foil version additionally fixed with a breathable mesh, resulting in a final size of $70 \times 30\ \mathrm{cm}^2$ for prototype 1, as shown in Fig. 1. Prototype 2 is shown in Fig. 2 and is slightly smaller at $72 \times 17\ \mathrm{cm}^2$. The actuators are attached to a base plate on the inside of the wraps in a 3D-printed housing via metal and plastic screws, so they can be replaced for testing.

3 Validation

3.1 Heat therapy

To validate the system, four different metrics from the product specification are of interest here:

1. Will the provided heat be in the range of 40 - 45 °C?
2. What is the maximum temperature and does it surpass 50 °C?
3. How long does it take for the system to reach 40 °C?
4. How good is the heat distribution?
5. How stable is the temperature after reaching the desired range?

To measure the temperature, type K thermocouples are used as sensors. Data points are collected every minute for 20 minutes and analyzed via Matlab. All of these tests are performed on the same person's left leg, with at least 10 minutes between runs to keep the measurements comparable. They are taken in the center of the heating element and with a layer of denim pants between the skin and the device. Both devices have a double layer of neoprene insulation over the first heating element to ensure the fit of the test subject. The room is at a constant temperature of 23 °C.

A selection of measured data for prototype 1 is shown in Fig. 3. It uses about 20 W of power, with the tests done at a voltage between the maximum value of 24 V down to 18 V which is provided by an external power supply. The desired temperature of 40 °C is set between 3 min 24 s and 5 min 20 s for maximum power output and between 7 min 20 s and 10 min for the 18 V run resulting in the maximal thermal time constant of t_1 = 6 min 19 s. None of them reaches more

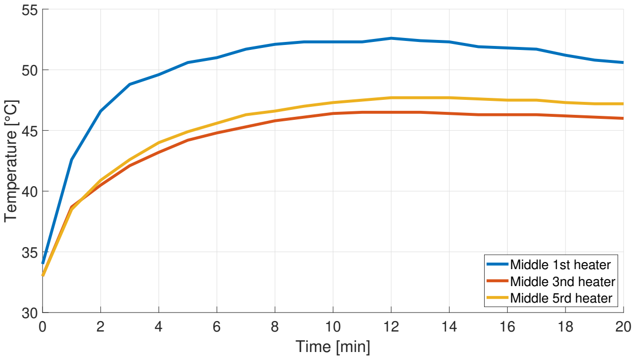

Fig. 4: Prototype 2: 1st,3rd,5th heater test on medium mode, 5 V Powerbank

than 50 °C and since the prototype has no form of supplemental heat distribution, only the three heating pads provide heat. They cover an area of 1091.25 cm^2, which is 52% of the total surface area. The selected data for prototype 2 can be seen in Fig. 4. It is powered by a USB power bank at full charge and has a power of 12 W. It has three preset power modes, but since the higher one quickly reaches over 60 °C and the lower one never reaches 40 °C, only the middle one is displayed. Here, the desired temperature of 40 °C is reached between 45 s and 1 min 50 s resulting in the maximal thermal time constant of t_2 = 1 min 9 s. The maximum temperature of 50 °C is reached by the first heating element with double insulation and peaks after 12 minutes at 52.6 °C. The subsequent drop in temperature is likely due to battery discharge. This prototype also does not have additional heat distribution and therefore has a combined heating area of 280 cm^2, 23% of the total surface area. Prototype 1 is capable of achieving the goal specifications and is selected as the heating system.

3.2 Focal vibration therapy

To validate the three actuators, a baseplate was designed on which the M352C65 piezoelectric accelerometer and one actuator are mounted using 3D-printed parts. The sensor signal is amplified and fed into the RTB2004 digital oscilloscope. The oscilloscope also supplies the AC current whcih then gets amplified up to 6 V to the LRA. The ERMs are powered by a laboratory power supply since the oscilloscope provides an insufficient output voltage range. In the test setup, a single person is tested on the left leg and in a seated position with a knee bend of 90° and the muscle in a rested state. All tests are performed with prototype 1, which is evaluated for these design specifications:

1. Frequency range between 20 - 170 Hz
2. Acceleration between 2 - 5 g

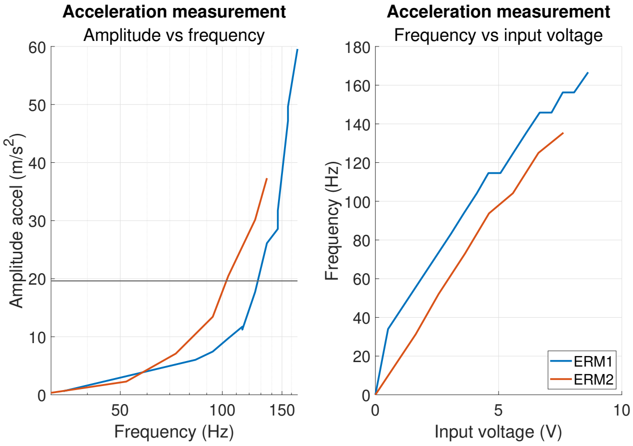

Fig. 5: Comparison between ERM1 and ERM2: Amplitude and Frequency for input of up to 9 V for ERM1 and 7.5 V for ERM2.

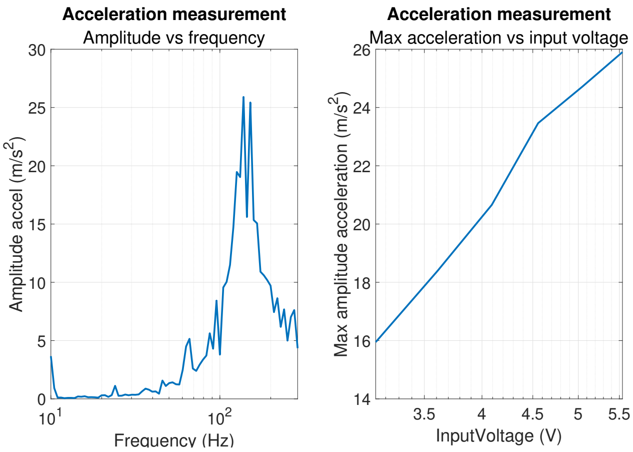

Fig. 6: LRA actuated between 0 and 300 Hz, with an input voltage between 1,26 and 2 V_{rms}.

3. Bandwidth of 40 Hz inside the given Acceleration and Frequency range

The results for the ERMs can be seen in Fig. 5. ERM 1 has a weight of 8 g and a size of 22 × 12 × 10 mm^3. The input voltage ranges from 1.5 - 9 V and has a rated current of 80 mA. In the test results shown, it covers a frequency range of 83 - 166 Hz with an acceleration of 0.6 - 6 g. The bandwidth over 2 g is just below 39 Hz, which is just below the desired specification.

ERM 2 has a weight of 16 g and a size of 27 × 15 × 12 mm^3. The input voltage ranges from 2.5 - 7,5 V and has a load current of 180 mA. In the test shown, it covers a frequency range of 73 - 135 Hz with an acceleration of 0.72 - 3.8 g. The bandwidth over 2 g is just below 35 Hz, which is also just below the desired specification.

The results for the LRA can be seen in Fig. 6. It weighs 8 g and has a size of 25 × 17 × 7 mm^3. It is AC-powered with a maximum input power of 1 W and a resonant frequency between 96 - 144 Hz. In the test results shown it is actuated between 0 - 300 Hz with an input power of 1.26 - 2 V_{rms}, corresponding to 3.1 - 5.5 V. The maximum acceleration is between 1.6 - 2.6 g and the bandwidth over 2 g is 24 Hz.

3.3 Statistical validation

While testing there is some variation in acceleration caused by how tight the device is wrapped around the leg. To get a better understanding of this variation three tests are done on six different people using both ERMs and Prototype 1. The group ranges from 22 - 35 years in age, 55 - 95 kg, and consists of one female and five males. Everyone is told to wrap the device tightly around their right leg. The current is adjusted so the frequency of the system is at 110 Hz using the displayed data on the oscilloscope. The tested person is then asked to remain as still as possible in three separate positions while three data points are collected at each position with an interval of five seconds in between. The first position is sitting down with the leg stretched out and resting on a slightly elevated position. For the second position, the knee is bent to 90°. The last position is standing. The supplied voltage does not change during the test and the order of the positions is always the same. This is done to see the deviation of the actuator performance between different people and in different positions and repeated again with the heating element turned fully on to see a possible influence. The results can be seen in Fig. 7. For these tests,

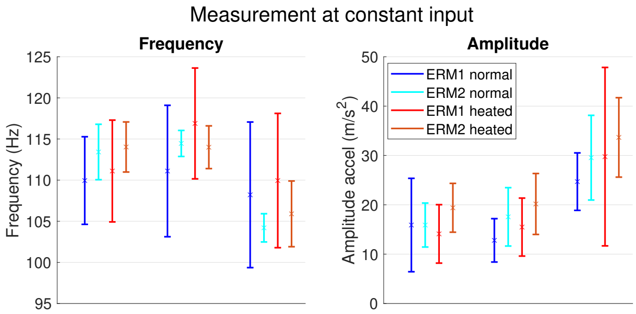

Fig. 7: Standard deviation of frequency and amplitude for tests without (blue) and with (red) heater on on six different people. Left is with a stretched leg, middle with the knee at 90°, and right is standing up.

ERM 2 clearly outperformed ERM 1, with an average standard deviation of 2.7 Hz and 6.3 $m s^{-2}$ compared to 7.2 Hz and 8.2 $m s^{-2}$. The outcome on the heated test did change slightly for positions one and two and doubled for position three, but the deviation is still in an acceptable range compared to ERM 1. The changes could be caused by actuator performance under heat, but could also be caused by variations in fit of the device in between runs.

4 Conclusion

In this work, a very cost-effecive system for heat and focal therapy is developed. The weight of the system is only 328 g, which is very good for a portable system. The system is equipped with a simple 9 V Battery and a potentiometer to power the actuators. A future version will feature a revised version of Prototype 2 to also make the heating system portable. The small actuator and sensor help the user to have a better feeling when wearing the device. The frequency and acceleration range is in a suitable range for the body. Since the provided heat, maximum temperature and heated area are all in a range suitable for the body, and only one heating element does not reach the target temperature in less than 5 minutes, the heating system ultimately performed better than the vibration system. All tested persons described the experience as pleasant.

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