Good Vibrations: An Evaluation of Vibrotactile Impedance Matching for Low Power Wearable Applications

Jack I.C. Lindsay[1,2], Iris Jiang[1], Eric Larson[2], Richard Adams[3], Shwetak N. Patel[2], Blake Hannaford[1]

[1]BioRobotics Lab
[2]Ubicomp Lab
University of Washington
Seattle, WA
{JackICL, IJiang, ECLarson, Shwetak, Blake}@uw.edu

[3]Barron Associates
Charlottesville, VA
{Adams}@barron-associates.com

ABSTRACT

Vibrotactile devices suffer from poor energy efficiency, arising from a mismatch between the device and the impedance of the human skin. This results in over-sized actuators and excessive power consumption, and prevents development of more sophisticated, miniaturized and low-power mobile tactile devices. In this paper, we present the experimental evaluation of a vibrotactile system designed to match the impedance of the skin to the impedance of the actuator. This system is able to quadruple the motion of the skin without increasing power consumption, and produce sensations equivalent to a standard system while consuming 2/3 of the power. By greatly reducing the size and power constraints of vibrotactile actuators, this technology offers a means to realize more sophisticated, smaller haptic devices for the user interface community.

ACM Classification:

H.5.2 [Information interfaces and presentation]: User Interfaces. – Haptic I/O.

Author Keywords

Haptics; Vibrotactile; Vibration Motors

INTRODUCTION

Vibrotacile actuators are used ubiquitously for haptic feedback—they are built into every smartphone and modern game controller and are used for everything from notification to tactile feedback. Most vibrotactile actuators accelerate a mass back and forth at high frequency to produce vibration. These actuators offer a simple means of conveying tactile cues to users, and can be built into large arrays for more sophisticated haptic rendering [1], [2]. However, the perceptibility of haptic sensations is limited by the size of the vibrating mass, and consequently, the power consumption required to move that mass. This means that miniaturized haptic feedback systems and power-limited mobile devices can only produce a fraction of the possible haptic sensations afforded by vibrotactile actuators.

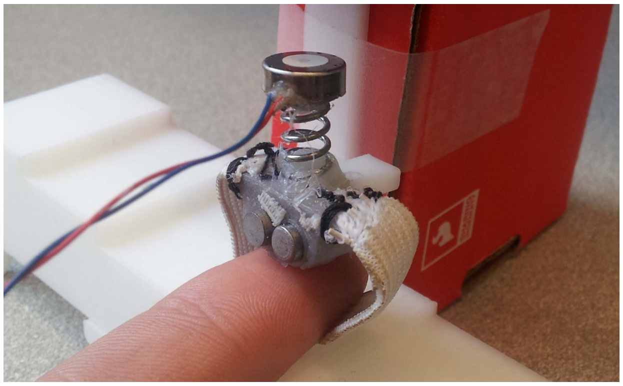

Figure 1. The prototype impedance adapter in test setup for displacement measurement.

Overcoming these limitations requires shrinking actuators and cutting power consumption. Unfortunately, vibrotactile devices are fundamentally constrained by the skin's vibrotactile threshold, or the threshold below which vibrations are imperceptible. Surpassing the vibrotactile threshold places constraints on the minimum size of the motor mass and its acceleration. Moreover, as the number of actuators and vibration levels increases, these systems require even more power and size. Because of the relationship between perception, vibration, and power, researchers have recently attempted to maximize transmission of energy from the actuator to the skin.

For instance, Jiang *et al*. use an elastic support structure to manage the load to the motor [2] and increase skin displacement. This system is appropriate for applications like lower leg prosthetics, but is not suitable for tactile stimulation of the hands and fingers in mobile devices because the system requires a large surrounding structure.

In our system, we adopt the theoretical framework of [3], which describes the design of an impedance adapter for optimizing the energy transfer to the skin from a vibrotactile actuator (*i.e.*, using a small motor with minimal

UIST'13, October 08 - 11 2013, St Andrews, United Kingdom

ACM 978-1-4503-2268-3/13/10…$15.00.
http://dx.doi.org/10.1145/2501988.2502051

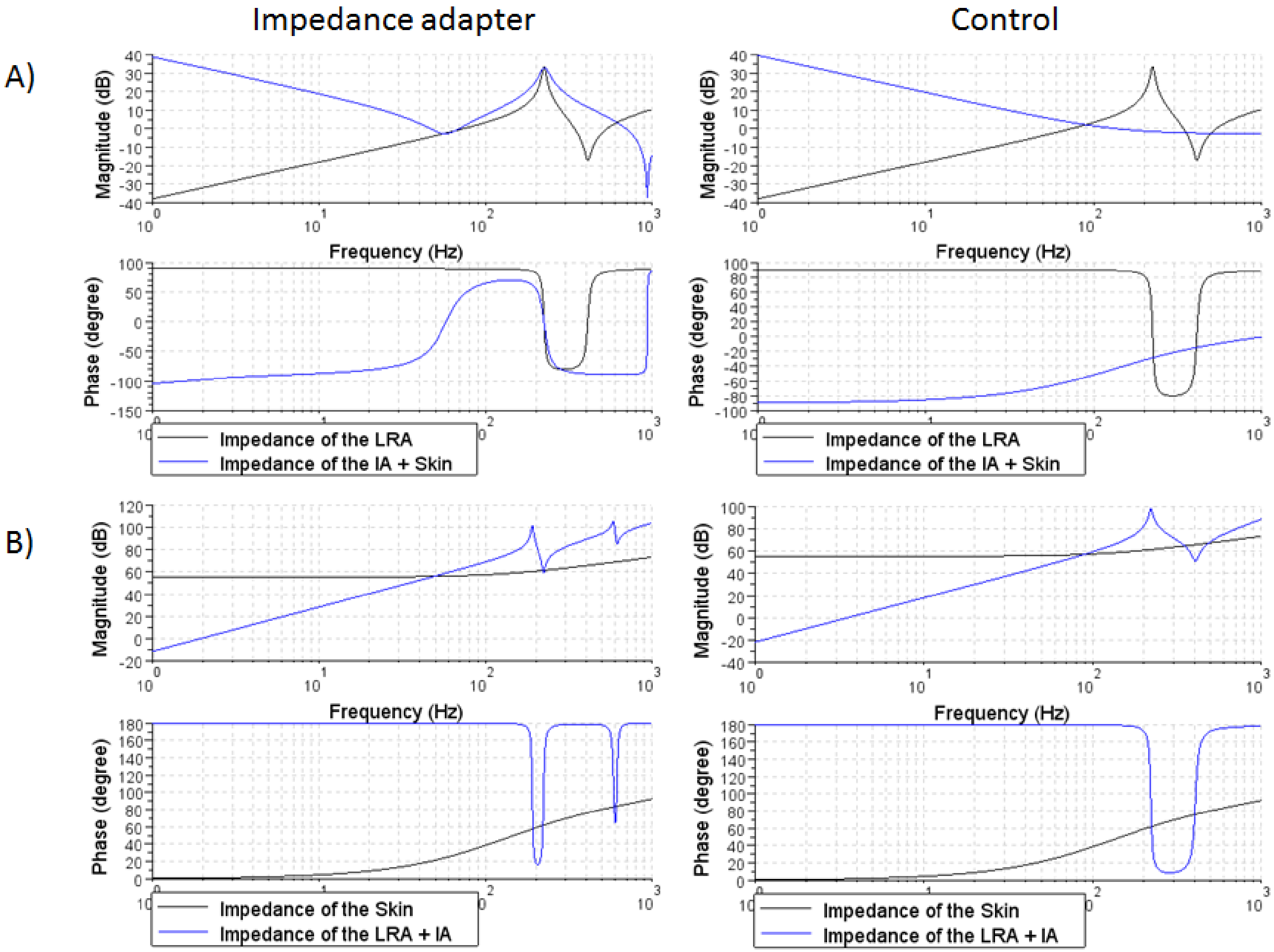

Figure 2. Bode plots of the impedance of different elements of the system. A) Impedance at the interface of the LRA and impedance adapter. B) Impedance at the interface of the impedance adapter and skin. Modeling of the impedance of the control system is performed by setting IA parameters such that it appears as a rigid, massless sheet without damping.

power input). The impedance adapter works in series with the actuator (*i.e.*, it can be worn on the finger or embedded underneath the actuator). This is in contrast to Jiang *et al.* who required the structure around the motor. Applications for this technology include virtual and augmented reality gloves with increased dexterity, rendering fine textures on touch surfaces, and increased haptic capability in numerous mobile devices. The impedance adapter offers a means to greatly miniaturize the size and power of vibrotactile feedback without sacrificing functionality.

In this paper, we describe the implementation of a working prototype and an empirical evaluation of our prototype system with eight users. Our device consists of a mass and spring that match the impedance of the skin to the impedance of the actuator. Our results show a significant decrease in power consumption, and our adapter can generate a four-fold increase in skin displacement. Furthermore, our system can generate vibration on the skin that is perceptually equivalent to a system without an impedance adapter at two-thirds the power—thus increasing the range of haptic sensation in small, wearable devices.

Our contributions are two-fold. We present:

1. A physical prototype of a haptics impedance adapter that is informed by the mathematical model described in [3].

2. An empirical evaluation of the device quantifying skin displacement and the perceived haptic sensation.

Our system places energy transfer as a major priority in haptic design, and stands as a first round prototype in a field that could continue to lead to smaller haptic devices.

THEORY OF OPERATION

In typical operation, vibrotactile actuators supply energy to the skin by producing waves of force directly at the skin's surface. These waves interact with the impedance of the skin, and are either absorbed into the skin through damping or reflected back off. In existing systems, the skin's impedance is significantly different from that of the actuator, and large amounts of energy are reflected backwards and lost, and therefore do not contribute to perception.

The impedance adapter works as a matching network that takes the waves of vibration from the actuator and conditions them to match the impedance of the skin. The matching network has an impedance which matches both the LRA and the skin at their respective interfaces at the operating frequency, as shown in figure 2. This greatly reduces energy reflection, increasing energy absorption and resulting in greater perception. See [3] for a summary of the impedance modeling.

PROTOTYPE AND IMPLEMENTATION DETAILS

Two prototypes were created with different contact areas. This was because simulation results from [3] indicate that maximum displacement is achieved using a contact area of 1 mm^2, while maximum sensation was achieved using a contact area of 64 mm^2. Both impedance adapters include a Precision Microdrives C-10 linear resonant actuator (LRA), a steel compression spring, a plastic base, steel dowel pins, and elastic band 1.25cm wide (see Figure 3). The steel compression spring was cut to length from stock, and its new spring constant was measured. The plastic base was 3D printed and included a mount for the dowel pins, spring, and elastic band. Furthermore, the base had a carefully measured area in contact with the skin. Impedance adapter 1 (IA#1) had a contact area of 64 mm^2 and impedance adapter 2 (IA#2) had a contact area of 1 mm^2. Both plastic bases were fitted with two dowel pins, and weighed 4.6g including the pins.

The complete assembly consisted of the LRA, spring, and base in series with the skin as shown in Figure 3. The elastic band was sewn to the base and wrapped around the finger.

Based on [3] we hypothesized that IA#1 would increase perceived sensation by a factor of 2.5 and IA#2 would produce a four-fold increase in skin displacement.

EXPERIMENTAL EVALUATION

We designed two experiments that evaluated (1) the skin displacement between an impedance adapter and a control and (2) the power requirements for the impedance adapters to provide equivalent perceived sensation as compared to a vibrotactile control.

Skin Displacement

In this evaluation we measured the movement of the skin in response to the actuator with and without the impedance adapter. Skin displacement was measured using a Keyence IL-030 laser distance sensor, which provides a resolution of 0.001mm.

Experiment. In the control condition the laser was focused on the top of the LRA, with the finger directly in contact with the LRA. The finger was assumed to be in constant contact with the LRA. When the impedance adapter was present, the laser was focused on the plastic base sitting directly on the skin. The base was again assumed to be in constant contact with the skin. The base was thick enough that any flex was assumed to be small in comparison to the oscillation of the system, see Figure 1.

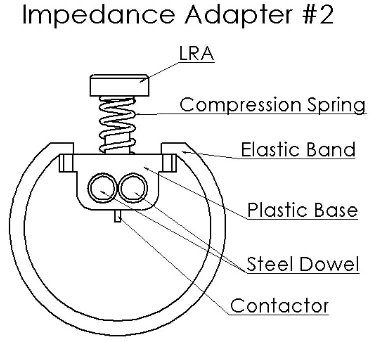

Figure 3. Schematic diagram of an impedance adapter and LRA. The finger is placed through the loop of the elastic band.

In all conditions, the vibrating system was held in contact with the skin using an elastic band. The elastic was sized to loosely hold the system in place, and designed to minimize static pressure against the fingerpad. Paper shims were used to ensure the oversized band fit evenly across participants. The band experienced very little stretch when properly shimmed, and most of the static pressure on the skin was a result of the weight of the impedance adapter and LRA. With a total mass of 7.5g the impedance adapter system produced a gravitational force on the finger of 0.06N, resulting in a displacement of ~0.75mm. However, this displacement should not affect the properties of the finger—other studies have found that this level of static pressure has a minimal effect on the mechanical impedance of the fingertip [4]. Furthermore, work by Lamore and Keemink found no difference in the vibrotactile threshold at high frequencies between static loading conditions [5]. Thus the gravitational force should have no effect on the experiments.

Skin displacement was measured using a stock LRA, an LRA with a 1.1 mm^2 contact area, and both impedance adapters. Eight subjects (four female, four male) were tested in all four conditions, three trials per condition. All tests were conducted using the participant's index finger. The study was approved by the University of Washington Human Subjects Division, approval #44695. The data from the distance sensor were band-pass filtered in the frequency range of interest (20-500Hz) to remove hand tremor and high frequency noise. We then calculated the root-mean-square (RMS) skin displacement for each trial using the filtered data.

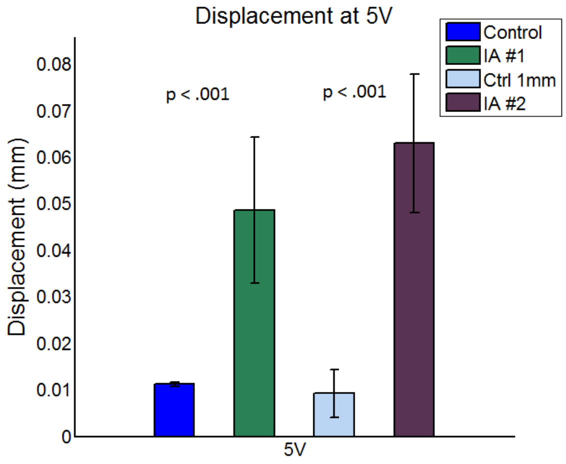

Figure 4: (A) RMS skin displacement for a contactor with a radius >4.5mm. (B) RMS skin displacement for a contactor with a radius of 1mm

Result. IA#1 and IA#2 were able to significantly increase skin displacement as compared to a stock LRA by a factor of 3.26 and 4.25 on average, respectively (based on a paired t-test, $p<0.001$). The mean RMS displacement and standard deviation for all conditions is shown in figure 4.

Implication. Simulations in [3] expected IA#2 to outperform the stock LRA by a factor of 4.40 which is remarkably close to the empirical finding of a 4.25x improvement. IA#1 fared even better than simulation, with an expected improvement of 2.28x and a measured improvement of 3.26x. This demonstrates an error in the model in [3], and suggests that mechanical stiffness and damping do not increase as a 1/3 power law of contact area.

Previous studies in psychophysics have demonstrated that displacement is proportional to sensation, all else being held equal [7]. Thus, doubling displacement will double sensation. With these large gains in skin displacement, we also set out to measure the perceived sensation of these gains in a controlled user study.

Equivalent Perception

All eight subjects also participated in a perceptual equivalence test. Each subject wore the stock LRA on their right index finger. This was used as the reference. On the left index finger, subjects wore one of the four test conditions: a stock LRA, an LRA with 1.1mm^2 contact area, IA#1, or IA#2. Subjects were instructed to try and match the vibration level felt on the left finger with the vibration felt on the reference finger.

Experiment. The actuators were driven by two separate power supplies. The experimenter would set the voltage of the reference actuator to 1 of 5 settings (1V, 2V, 3V, 4V, or 5V), and provide ~1sec bursts of vibration to both actuators at the same time. Both actuators vibrated at a constant frequency of 175Hz. Subjects would tell the experimenter whether they felt the voltage of the test actuator should be higher or lower, and the experimenter would adjust the voltage of the test actuator until the subject perceived both actuators to feel the same. Subjects wore earmuffs to block the sound of the vibration and were positioned so they could not see the voltage readings on the power supplies.

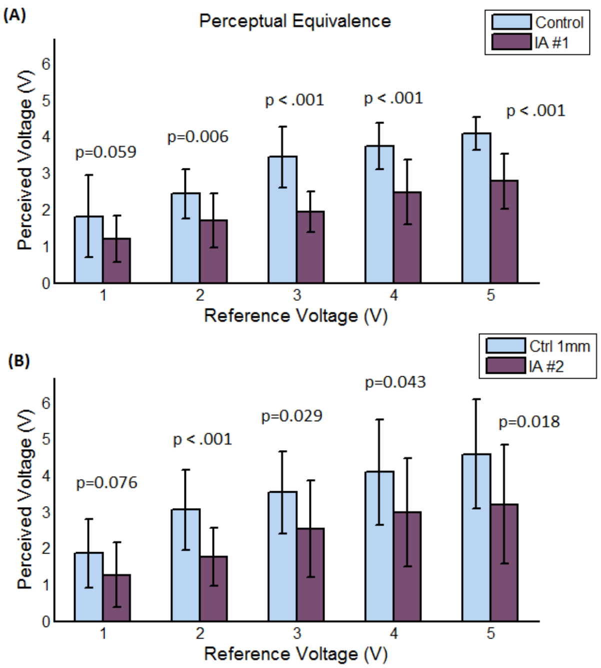

Figure 5. Subjects adjust voltage levels on an LRA on one index finger to match the vibration sensed from an LRA on the other index finger. (A) Shows tests with a large radius, (B) shows tests with a smaller radius.

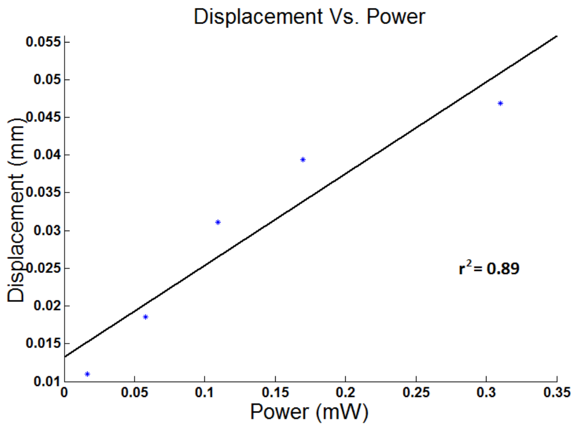

Figure 6: Linearity of the LRA and impedance adapter at power levels.

Each of the four test conditions was presented in random order. Each voltage level within a test condition was also presented in a random order. It condition consisted of 10 trials (2 trials per voltage level).

Result. The results of the perceptual equivalence study are shown below in figure 5. Figure 5 (A) compares IA#1 to the LRA with the same 64mm^2 contact area. Figure 5 (B) compares IA#2 to the LRA with the same $1mm^2$ contact area. The results show that subjects set the test voltage 35% lower on average for IA#1 and 32% lower on average for IA#2 than the reference voltage applied to a stock LRA. There was no statistically significant difference between the reference voltages and the test voltages for either control condition.

Subjects' evaluation of equivalent voltage settings varied between low reference voltages and high reference voltages. With a 1V reference, it was not clear whether subjects could distinguish between a system with an impedance adapter and a system without. In both conditions, however, subjects could distinguish between the two systems when the reference voltage was 2V or higher, and subjects applied a significantly lower voltage to the system with an impedance adapter ($p < 0.05$).

Implication. In all cases, the voltage for the system with an impedance adapter was set at approximately 66% of the voltage for the system without an impedance adapter. This suggests that an impedance adapter can be used to lower power consumption by 55% while maintained an equivalent psychophysical sensation. Even so, this is a lower percentage than might be expected based on psychophysical tests by [7], who found a linear relationship between depth of indentation and stimulation. This suggests that the four-fold increase in skin displacement should have resulted in a 75% drop in equivalent power, given a linear relationship between power and displacement.

This difference could be attributed to subjects' inability to discriminate between small changes in voltage level [8]. For instance, when adjusting voltage levels to be equivalent, if the voltage was initially low, the subject would generally say to stop adjusting the voltage at a lower level. If the voltage was initially set high, then the subject would say to stop at a higher voltage. Thus, "equivalence" in our experiments may be artificially high—the true equivalence level for minimizing the power could be ascertained by always adjusting the voltage level up from a lower voltage.

However, the difference could also be attributed to non-linear dynamics in the LRA and impedance adapter at low power levels. To test this latter hypothesis, two subjects participated in a skin displacement test using IA#1 as input voltage was swept from 1V to 5V. The results are shown in Figure 6, illustrating a linear relationship between power and displacement. Thus, the discrepancy in theorized power reduction and actual power reduction is not due to non-linearity in the LRA. It is more likely due to the "resolution" at which subjects could perceive the vibrotactile sensation. Therefore we believe these results show a "worst case" power reduction. The possible power savings are likely much greater than 55% (and might be as high as the theorized 75%).

MINIATURIZATION

The current prototypes are quite large, requiring significantly more volume than a vibrotactile actuator alone. The prototypes, however, are just one realization of the model developed in [3], designed to evaluate whether the simulation results showing improved skin displacement holds up in the real world. The four parameters upon which they are designed could be realized in a much smaller package with a membrane spring and dense masses. Physical constraints allow the design to shrink to less than half the volume of the LRA while still maintaining proper characteristics.

CONCLUSION

Empirical testing of our prototype impedance adapters has demonstrated the significant improvement they offer over a typical system. By matching the impedance of the skin to signal from the actuator, it is possible to greater improve skin displacement—up to a four-fold. We were also able to show the "worst case" power reduction was 55%. In the future, we will make the prototype even smaller as the properties of the impedance adapter depend only on the stiffness of the spring and the mass of the base.

REFERENCES

1. Zelek, J. S., Bromley, S., Asmar, D., & Thompson, D. (2003). A haptic glove as a tactile-vision sensory substitution for wayfinding. *Journal of Visual Impairment and Blindness*, 97(10), 621-632.
2. Jiang, I., Ishikawa, Y., Lindsay, J., Hannaford, B. Design and Optimization of Support Structures for Tactile Feedback, *IEEE World Haptics Conference*, Daejeon, Korea, 2013, In Press.
3. Lindsay, J., Adams, R., and Hannaford, B., Improving Tactile Feedback with an Impedance Adapter, *IEEE World Haptics Conference*, Daejeon, Korea, 2013.
4. Precision MicroDrives, www.precisionmicrodrives.com
5. Moore, T. J., & Mundie, J. R. (1972). Measurement of specific mechanical impedance of the skin: Effects of static force, site of stimulation, area of probe, and presence of a surround. *The Journal of the Acoustical Society of America*, 52, 577.
6. Lamoré, P. J. J., & Keemink, C. J. (1988). Evidence for different types of mechanoreceptors from measurements of the psychophysical threshold for vibrations under different stimulation conditions. *JASA*, 83, 2339.
7. Verrillo, R. T., Fraioli, A. J., & Smith, R. L. (1969). Sensation magnitude of vibrotactile stimuli. *Perception & Psychophysics*, 6(6), 366-372.
8. Gescheider, G. A., Bolanowski, S. J., Hardick, K.R., (2001). The frequency selectivity of information-processing channels in the tactile sensory system. *Somatosensory & Motor Research*, 18(3), 191-201.