**Third Joint Eurohaptics Conference and Symposium on Haptic Interfaces
for Virtual Environment and Teleoperator Systems
Salt Lake City, UT, USA, March 18-20, 2009**

Compact and Low-Cost Tendon Vibrator
for Inducing Proprioceptive Illusions

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ABSTRACT

Recent literature suggests that inducing proprioceptive movement illusions with predefined movement trajectories via tendon vibration requires use of multiple vibrators and precisely controlled frequency profiles. In this study, we report the design, modeling and control of a compact, low-cost tendon vibrator and illustrate its capability of accurately following time-varying frequency profiles. During the demonstration, participants will test the vibrator to experience illusory elbow flexion.

1 INTRODUCTION

It has been known for several decades that vibrating a muscle tendon within a certain frequency range induces realistic movement illusions at the corresponding joint [2]. This phenomenon has drawn the interest of the research community, however most of the studies so far utilized tendon vibration as a tool for investigating the mechanisms that underlie proprioception.

Although inducing the proprioceptive illusions is relatively easy, it is very difficult to generate controlled sensations due to the inconsistency and instability of the illusion, differences observed among subjects, muscle configuration, and load conditions, among other reasons. Our ultimate goal is to induce accurately controlled illusory sensations via tendon vibration. We believe that achieving this goal will open the way to a huge number of potential applications in the fields of haptics, virtual reality, smart prosthetics, rehabilitation, motor adaptation and skill learning.

Recently it was demonstrated by Albert *et al.* [1] that it was possible to induce a sensation of moving along a predefined trajectory fairly consistently and clearly. They achieved this sensation by using multiple vibrators on the complete set of muscle tendons around an ankle joint and playing back the frequency profiles that are based on previously recorded Ia afferent patterns during a passive trajectory following movement of the same joint. In the same study, it was shown that the frequency range of the vibrations linearly correlated with the size of the trajectory that was displayed. We interpret these findings as being highly encouraging towards our ultimate goal. Key points in the success of the study by J-P. Roll's group [1] were

- Accurate placement of vibrator heads on tendons by determining the locations where the induced illusion "matched with the known preferred sensory direction of the particular muscle".

- Use of multiple vibrators to cover the whole set of muscles accountable for the movement of the joint under consideration.

- Use of time-varying frequency profiles that resembled the Ia afferent signal profiles instead of constant frequency signals.

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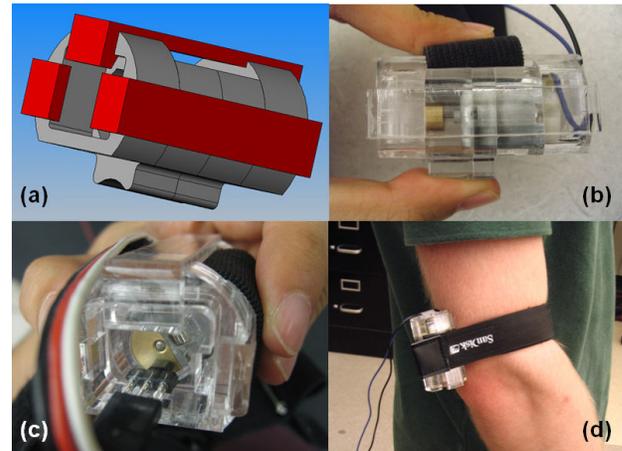§e-mail: shewokis@drexel.edu

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Figure 1: (a) 3D model of the designed vibrator casing. (b) Actual acrylic casing with the motor and the arm-band installed (sensor not installed). (c) Hall-effect sensor and the magnet for sensing the rotational speed of the motor. (d) Vibrator worn on the triceps brachii tendon (sensor not installed).

In order to replicate this success in an "out-of-the-lab" environment, tendon vibrators that are compact, attachable to the body in a simple way (such as strapping) and yet capable of precisely generating the required time-varying frequency profiles are required. In this demonstration paper, we report the design, system identification and feedback control of a low-cost tendon vibrator.

2 VIBRATOR DESIGN

Pager motors and small vibration motors, which consist of an unbalanced mass attached to the shaft of a small permanent magnet DC motor, constitute very low-cost actuators for vibration. We have used a Panasonic vibration motor (micro-motor with dimensions $0.59" \times 0.79" \times 1.15"$) with an operating range up to approximately 150 Hz. Frequency and amplitude of vibrations generated by a vibration motor are coupled and can not be controlled separately, *ie.* frequency of vibration dictates its amplitude. It was reported by Naito et. al [4] that although some qualitative aspects of the illusion were affected by the amplitude of vibration, it was possible to induce the vibration with amplitudes ranging from 0.2 mm to 3 mm. The study by Albert *et al.* [1] reports an amplitude of 0.125 mm. Therefore the fact that the amplitude of the vibration is not as important as the frequency renders vibration motors as appropriate actuators for tendon vibration. In fact, most of the physiotherapy vibrators frequently used in tendon vibration studies also use vibration motors.

We have designed a casing for the vibrator to allow a port for the attachment of an elastic arm-band, and to provide a contact region to carry the vibrations to the tendon. The casing is manufactured out of acrylic by laser cutting and consists of all snap-on pieces with no fasteners or glue, as can be seen in Figures 1a and 1b. The

surface area of the head in contact with the skin and the tendon can be adjusted by stacking pieces with different profiles. The vibrator worn on the triceps brachii tendon near the elbow is shown in Figure 1d.

A cap for the case holds a Hall-effect sensor against a small magnet, carried by another cap that fits on the unbalanced mass, as shown in Figure 1c. This sensor setup provides a way to measure the rotational speed of the motor shaft. The output of the sensor is amplified and fed into a frequency-to-voltage converter circuit. Output of the converter is filtered by a second-order Butterworth filter circuit to remove induced high frequency ripples. An oscil-loscope reading of the period of the amplified and filtered sensor output signal is used to obtain the calibration between filtered sensor voltage and vibration frequency. A power op-amp is used to drive the vibration motor.

3 MODELING, MODEL VERIFICATION AND CONTROL

A National Instruments PXI machine with a PXI-6070E data acquisition card and Labview 8.2 software is used to read the filtered voltage and command the voltage to the amplifier. The sampling rate was set at 200 Hz during both identification and control phases.

A permanent magnet DC motor has a voltage-to-speed transfer function (TF) that is of second order with no zeros in the continuous domain [3]. When discretized the TF will have a zero and two poles in the discrete domain. Allowing for an output delay (mostly caused by the converter and the filtering in our case) in the model gives us the final model structure of

$$\frac{Y(z)}{U(z)} = \frac{b_1 + b_2 z^{-1}}{1 + a_1 z^{-1} + a_2 z^{-2}} z^{-n_d} \quad (1)$$

where n_d represents in integer order of the delay. We used a data set of one minute length consisting of a modified pseudo-random binary signal (PRBS) that took values of only 3 and 7 V and the corresponding recorded output for parameter estimation. First half of the data set was used for estimation and the remaining part was used for validation. We utilized System Identification Toolbox of MATLAB to conduct the least squares estimation with different delay orders, and satisfactory results were obtained for a model with $n_d = 14$, in terms of the percent match between the simulated and actual output values in an L2 norm sense, for both the estimation (86.45% fit) and validation (69.06% fit) data sets. Hence the final TF of the tendon vibrator with the sensor was found to be

$$\frac{Y(z)}{U(z)} = \frac{0.002727z - 0.002107}{z^2 - 1.948z + 0.9492} z^{-13} \quad (2)$$

The estimated output delay value of 13 sampling periods (65 msec) was in agreement with the observations from the recorded data. Since the delay was very small, we first designed a discrete PI controller by ignoring the time-delay, which performed well for step input, as can be seen in Figure 2a.

However, the same PI controller was not able to control the system properly for a ramp reference input. The use of Padé approximation [6] for the delay to obtain a non-transcendental plant TF was inconclusive due to an unstable zero -introduced by the approximation- making it impossible to achieve a reasonably good response. We eventually settled with a Smith predictor control structure [5]. The Smith predictor effectively carries the output delay out of the feedback loop so that the performance of the controller designed for a plant without the output delay is mostly (depending on how accurate the plant model is) preserved for the system with the delay. The trade-off is getting a controlled output that is delayed by the amount of the output delay of the plant, which for a delay of 65 msec is acceptable. The performance of the PID controller with a ramp and an exponentially increasing frequency profiles to be tracked by the vibrator can be seen in Figures 2b and 2c, respectively.
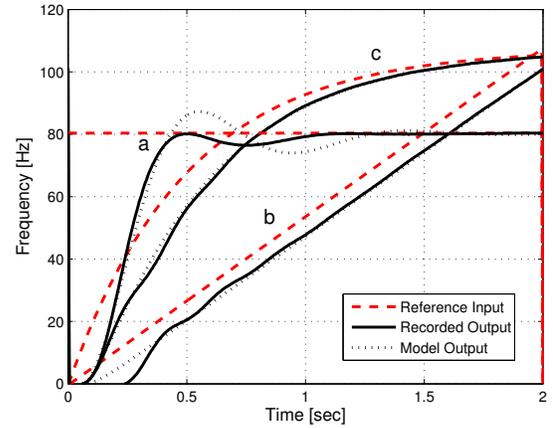

Figure 2: Feedback-controlled responses of the model and the actual vibrator (a) Step response. (b) Ramp response. (c) Exponential profile response.

4 DEMONSTRATION

The demonstration will allow participants to test the developed tendon vibrator on their triceps brachii tendon right above the elbow. Participants will feel the illusion of elbow flexion due to vibrations and will be able to experiment with various time-varying frequency profiles and test the corresponding induced illusions.

5 CONCLUSION

Mechanical and controller design of a low-cost and compact tendon vibrator is presented. The total cost of the developed tendon vibrator (excluding the control hardware and software) is approximately $20. Despite its low cost, the vibrator has the capability to accurately generate any desired time-varying vibration profile. Future work will utilize the vibrator with the ultimate goal of inducing controlled illusory proprioceptive sensations. We are developing a vibrator for the biceps brachii muscle as well and looking into more compact designs utilizing pager motors. One apparent application would be implementation of artificial proprioception on prosthetic devices, however we believe that it can find applications in many additional areas pertinent to haptics and virtual reality.

ACKNOWLEDGEMENTS

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