

Muscle-Propelled Force Feedback: Bringing Force Feedback to Mobile Devices

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ABSTRACT

Force feedback devices resist miniaturization, because they require physical motors and mechanics. We propose *mobile* force feedback by eliminating motors and instead actuating the user's muscles using electrical stimulation. Without the motors, we obtain substantially smaller and more energy-efficient devices. We present a prototype that fits on the back of a mobile phone. It actuates users' forearm muscles via four electrodes, which causes users' muscles to contract involuntarily, so that they tilt the device sideways. As users resist this motion using their *other* arm, they perceive force feedback. We demonstrate the interaction at the example of an interactive videogame in which users steer an airplane through winds rendered using force feedback. In a first user study, we found our device to cause users to produce up to 18.7N of force, when used to actuate their palm flexors. In a second study, participants played the video game described above; all ten participants reported to prefer the experience of muscle-propelled force feedback to vibrotactile feedback.

Author Keywords: mobile; force feedback; EMS.

ACM Classification Keywords: H.5.2 [Information interfaces and presentation]: User Interfaces. - Graphical user interfaces.

General Terms: Design; Human Factors.

INTRODUCTION

Force feedback has been used to enable eyes-free targeting [18], to increase task realism [1], and to enhance immersion in video games [20]. For such applications, force feedback is preferred over vibrotactile, because it provides physical forces that can counter the users' movements, providing a strong haptic sensation [19].

Recent research has started to create increasingly smaller force feedback devices, such as deformable devices (e.g., *SqueezeBlock* [5]), or motor-based devices using pulleys (e.g., *FlexTensor* [17]). What limits researchers' miniaturization efforts, though, is that it involves physical actuators that are hard to scale down while maintaining force [19].

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Figure 1: Our prototype electrically stimulates the user's arm muscles via the shown electrodes, causing the user to involuntarily tilt the device. As he is countering this force, he perceives force feedback.

In this paper, we attempt to push this evolution forward with the ultimate goal of bringing force feedback to mobile devices. In order to achieve this, we explore using the user's muscle power as a replacement for motors. We actuate the user's muscles using electrical muscle stimulation (EMS), a technique first explored in the 60's and 70's [14] and more recently in *Possessed Hand* [16].

MUSCLE-PROPELLED FORCE FEEDBACK

Figure 1 illustrates the use of our mobile force feedback prototype, in a mobile gaming scenario. The device is mounted on the back of a mobile phone, and the player has connected it using two skin-electrodes to the palm flexor muscles of each of his forearms.

As shown in Figure 2, the game requires the user to steer an airplane through strong side winds by tilting the device.

Figure 3 illustrates how we produce force feedback. The device renders the winds by trying to tilt the device against the user's will (Figure 3b). It achieves this by stimulating muscle tissue in the user's arm through the electrodes, triggering an involuntary contraction. This causes the user's arms to tilt sideways and thus the device to tilt. Since the airplane is controlled by tilt, the involuntary tilting threatens to derail the airplane. To stay on course, players counter the actuation using the force of their *other* arm (Figure 3c). As we find in Study 2, players perceive this as force feedback.



Figure 2: Close-up of the video game from Figure 1: wind turbines create side-winds that derail the airplane. This is rendered as force-feedback by the device.

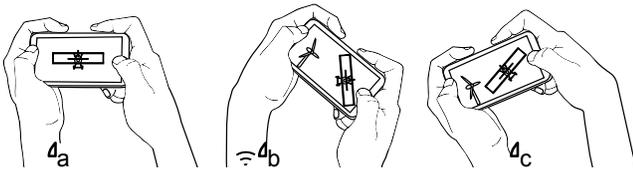


Figure 3: (a) As the user is playing (b) muscle-propelled force feedback kicks in, causing the user's left wrist to tilt the device. (c) The user responds by countering the forces, steering the plane against the wind.

DEVICE HARDWARE

The device induces involuntary muscle contraction by generating a biphasic waveform with a frequency of 25Hz and a pulse width of 290 μ s. Figure 4 shows a close-up of the hardware that produces this signal. The prototype measures 133mm \times 70mm \times 20mm and weighs 163g. It is comprised of an *arduino nano* microcontroller, which communicates via USB or Bluetooth with its host device, here an *HTC One X* mobile phone. The battery-powered signal generator is coupled to a medically compliant operational amplifier that outputs a maximum current of 50V/100mA over a 500 Ω load. Four reed relays allow us to map the signal to up to four channels.

BENEFITS AND CONTRIBUTION

Our main contribution is the concept of creating mobile force feedback using computer-controlled muscle stimulation. Our approach achieves miniaturization by (1) eliminating mechanical actuators, such as motors, and (2) substantially reducing battery size, as it is *two orders* of magnitude more energy-efficient to actuate a muscle (which receives its energy from the human body) than to drive a motor. In two simple user studies, we verify that our prototype creates sufficient force and that its effect is indeed perceived as force feedback.

On the flipside, setting up our device requires users to manually place electrodes, which requires knowledge about proper placement and a moment of time. Future prototypes may overcome these limitations and achieve an even smaller form factor by using implanted electrodes [6].

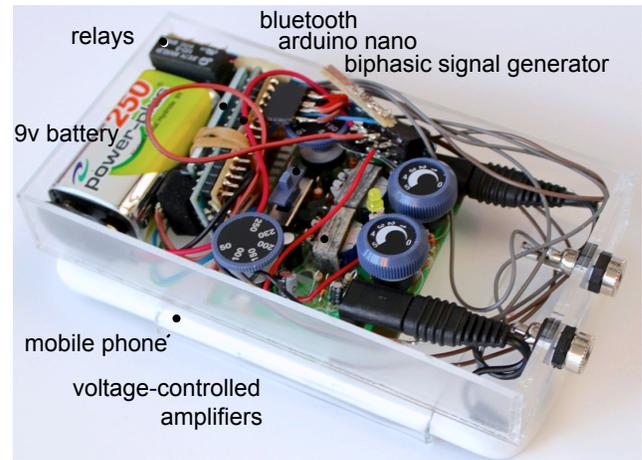


Figure 4: The backside of our prototype reveals its hardware design

RELATED WORK

Our work relates to force feedback and muscle stimulation.

Motor-based Force Feedback

Force feedback devices administer force to body joints mechanically, by pulley systems [11], exoskeletons [17], and more recently deformable interfaces [5]. An example of a pulley system is *SPIDAR* [11], which displaces the fingertip by pulling using motors. Exoskeletons include the *Utah Dextrous Hand Master* [8] or the *FlexTensor* [17], which require external apparatus to be mounted on the user.

Non-rigid actuation mechanisms include transmission of force by sound pressure [9] or air jets [15], even though these have not been shown yet to produce enough force to displace human joints. Force feedback is distinct from vibrotactile feedback in that it displaces joints.

Optimizing force feedback for size and weight

Force feedback devices that allow for a small form factor include deformable devices such as *MimicTile* [12], a flexible actuator placed on the side of a mobile phone that can dynamically regulate its stiffness using a shape memory alloy. *SqueezeBlock* [5] is a programmable spring device that provides force feedback while grasped. *InGen* [3] is a self-powered wireless rotary input device capable of force feedback. Finally, other approaches produce force momentum (i.e., torque) by mechanically moving a weight around, such as *GyroTab* [2] and Hemmert et al's device [7].

Electrical Muscle Stimulation (EMS) within HCI

Kruijff et al. manually induced muscle contractions in participants' biceps while playing videogames on a desktop computer [10]. In the same vein, Farbiz et al. used forearm stimulation to render the sensation of a racket hitting a ball in an augmented reality tennis game [4].

Recently, Tamaki et al. used EMS to actuate human fingers [16]. The technique targets situations where the user's input must be mediated or assisted, such as while learning to play a musical instrument. Unlike this assistive approach, our work *counters* the users' input, causing it to be perceived as force feedback.

STUDY 1: MEASURING GENERATED FORCE

To determine whether the approach delivers sufficient force, we evaluated the force of the muscular output induced by our prototype.

Participants

We recruited 10 right-handed participants (two female), between 24 and 50 years old ($M=31.2$ years old, $SD=9$ years). Participants had no prior experience with EMS. They received a small compensation for their time.

Apparatus and Procedure

As illustrated by Figure 5, the experimental apparatus actuated participant's wrist via disposable pre-gelled electrodes on the palm flexor muscles (*flexor carpi radialis* and partially the *flexor digitorum superficialis*) and measured the resulting force using a digital spring-scale.

First, we applied a sequence of test patterns to get the participant acquainted with EMS. Then, we calibrated an intensity range per participant: minimum intensity with visible contraction up to maximum intensity without causing pain.

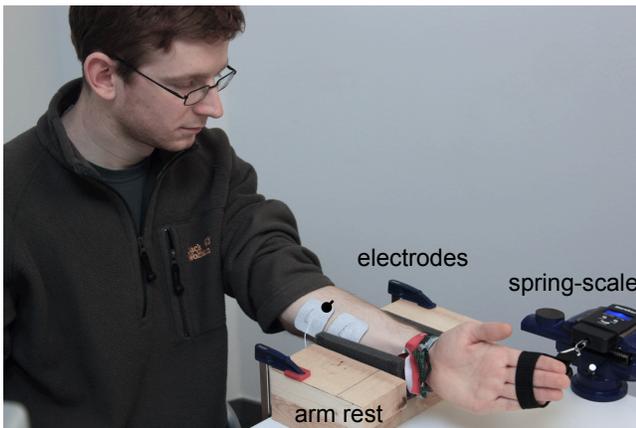


Figure 5: Apparatus for measuring the force of an induced involuntary contraction of the palm.

Task & Experimental Design

For each trial, participants were subjected to a stimulation pattern and we measured the resulting force they produced.

There were 6 stimulation pattern intensities (linearly interpolated between the two minimum and maximum intensity values determined during calibration) and 11 durations (50, 100, 200...1000ms). Overall, each participant performed a total of 132 trials: 6 (intensities) \times 11 (durations) \times 2 (repetitions).

Results and Discussion

Figure 6 shows the resulting forces across all users. The diagram shows that force grows with intensity level and is largely proportional to duration (average of SD on all data points = 79.57g). At 1000ms of highest intensity stimulation participants produced an average of 1903g (18.7N). An increase in duration generally caused an increase of force for intensity levels 2 to 6. For the lowest intensity, however, force tapered off for stimuli longer than 500ms.

For comparison, a Phantom force feedback device produces 3.3N [13]. Participants reached or exceeded this level for all intensities above 2 and stimulations longer than 400ms. This suggests that our prototype causes users to create sufficient force for typical force feedback applications.

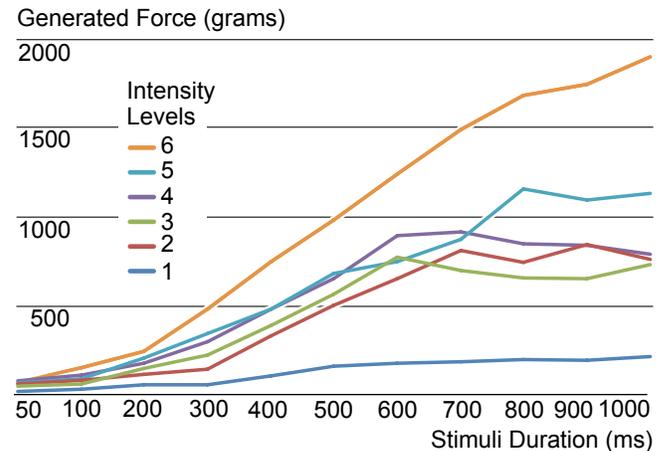


Figure 6: Average peak force (in grams) for palm flexion for different stimulation intensities (levels) and durations (in ms).

STUDY 2: MOBILE FORCE FEEDBACK GAMING

In this study, we investigated how participants *perceive* the force feedback generated by our prototype. Participants played the game described above. We compared the experimental muscle-propelled *force feedback* condition with a *vibrotactile* baseline.

Participants

We recruited 10 participants (3 females) between 20 and 40 years old ($M=27.4$ years old, $SD=5.4$ years), from which none had partaken in Study 1.

Task

To win the game (Figure 2), participants had to keep the airplane on-screen while collecting white clouds and avoiding black clouds. Staying on screen required them to resist the winds that “pushed the airplane off-screen”. Participants steered the airplane left and right by tilting the device. Touching the upper and lower half of the screen using their thumbs allowed participants to fly higher or lower.

Interfaces and Experimental Design

Prior to the study, participants were briefed about EMS and our device was calibrated to operate so as to produce visible contractions yet pain-free.

During the study (Figure 7), participants played the video-game with for at least 5 minutes per condition. In the *force feedback* condition, participants received feedback in the form of their screens tilting sideways under muscle actuation of both arms (i.e., both palm flexors). In the *vibrotactile* condition the direction of the wind was encoded using two different vibration patterns (participants were trained to correctly identify both patterns beforehand). The experiment used a within-subjects design and interface order was

counterbalanced. After completing each condition participants filled in a questionnaire comprised of several 5-point Likert scale questions.

Questionnaire Results and Discussion

Participants rated the game as more enjoyable when playing with *force feedback* (Mdn=4.5 of 5, IQR=1), than with *vibrotactile* (Mdn=3 of 5, IQR=2), which a Wilcoxon Signed-rank test showed to be of statistical significance ($Z=2.35$, $p=0.02$).

Participants rated the wind forces in the game as harder-to-counter when *force feedback* was active (Mdn=4.0 of 5, IQR=2) than in the *vibrotactile* condition (Mdn=1 of 5, IQR=1), which a Wilcoxon Signed-rank test confirmed to be of statistical significance ($Z=2.68$, $p=0.007$). Perceiving the direction such winds in the game showed no statistical difference from *force feedback* (Mdn=5 of 5, IQR=1) to *vibrotactile* condition (Mdn= 3 of 5, IQR=2).

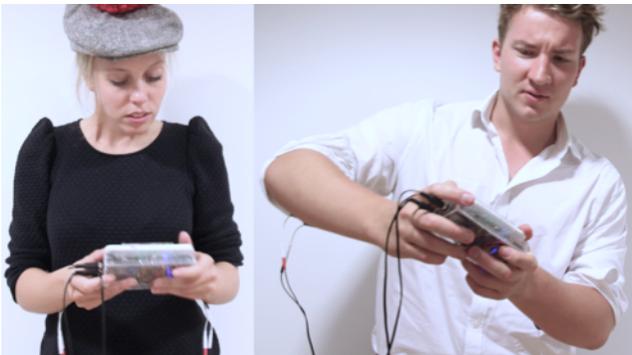


Figure 7: Participants from Study 2 experiencing the force feedback sensations delivered by our prototype.

All subjects expressed to prefer *force feedback* to *vibrotactile feedback*. Furthermore, participants' opinion suggested that *force feedback* contributed to a positive gaming experience (Mdn=4.5 of 5, IQR=1).

Participants' reactions during the *force feedback* condition suggested excitement and included positive comments about an increased sense of realism and immersion. All participants stated that the muscle-propelled *force feedback* condition was pain-free (Mdn=1 of 5, IQR=0).

CONCLUSION

In this paper, we demonstrated how to miniaturize force feedback by using electrical muscle stimulation. We demonstrated a mobile prototype and illustrated its effectiveness using a mobile gaming application. In two user studies, we found that the device generates up to 18.7N of force and contributes to an enjoyable mobile gaming experience.

As future work, we plan to explore non-gaming applications for muscle-propelled force feedback.

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