6-2011

Design of Body-Grounded Tactile Actuators for Playback of Human Physical Contact

Katherine J. Kuchenbecker
University of Pennsylvania, kuchenbe@seas.upenn.edu

Andrew A. Stanley
University of Pennsylvania

Recommended Citation

Kuchenbecker, Katherine J. and Stanley, Andrew A., "Design of Body-Grounded Tactile Actuators for Playback of Human Physical Contact" (2011). *Departmental Papers (MEAM)*. 288.
http://repository.upenn.edu/meam_papers/288

A. Stanley, K. J. Kuchenbecker. *Design of Body-Grounded Tactile Actuators for Playback of Human Physical Contact*. In Proceedings, IEEE World Haptics Conference, 563-568, June 2011. doi:10.1109/WHC.2011.5945547

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Design of Body-Grounded Tactile Actuators for Playback of Human Physical Contact

Andrew A. Stanley* Katherine J. Kuchenbecker†

Haptics Group, GRASP Laboratory
Department of Mechanical Engineering and Applied Mechanics
University of Pennsylvania, Philadelphia, USA

ABSTRACT

We present four wearable tactile actuators capable of recreating physical sensations commonly experienced in human interactions, including tapping on, dragging across, squeezing, and twisting an individual's wrist. In seeking to create tactile signals that feel natural and are easy to understand, we developed movement control interfaces to play back each of these forms of actual human physical contact. Through iterative design, prototyping, programming, and testing, each of these servo-motor-based mechanisms produces a signal that is gradable in magnitude, can be played in a variety of temporal patterns, is localizable to a small area of skin, and, for three of the four actuators, has an associated direction. Additionally, we have tried to design toward many of the characteristics that have made high frequency vibration the most common form of wearable tactile feedback, including low cost, light weight, comfort, and small size. Bolstered by largely positive comments from naive users during an informal testing session, we plan to continue improving these devices for future use in tactile motion guidance.

Index Terms: H.5.2 [Information Interfaces and Presentation]: User Interfaces—Haptic I/O

1 INTRODUCTION

Since Frank Geldard first suggested using tactile stimulation as a means of communication in 1960 [6], the sense of touch has developed into a valuable tool in the advancement of technology. While auditory and visual cues remain the most conventional methods of conveying information to a user, a handful of advantages have propelled the incorporation of tactile cues into various aspects of human-machine interfaces. The sense of touch allows private communication with a user via contact with the skin, whereas any visual or auditory events that a user could experience would also be perceptible to anyone else in close proximity. The sense of touch is also bidirectional in its ability to transmit information about both the user's actions on and perceptions of his or her surroundings. Furthermore, overuse of auditory and visual communication is likely to cloud the user's awareness and sensitivity to additional cues through those modalities, making tactile displays more salient and effective in complex environments [8].

Body-grounded tactile actuators collectively represent a particularly useful method for the presentation of tactile cues. On the continuum of haptic system design, they lie between classically grounded devices, which attach to a static object like a table as an inertial support, and ungrounded devices, which require no attachment to generate loads [4]. Devices grounded to the user's body apply equal and opposite forces at two separate locations, generating the illusion of directional torques or forces. In some cases, a small, body-grounded actuator with a large enough strap or grounding region can present the illusion of a single, unbalanced force acting at the contact point of the actuator. Thus, the mechanical design of these actuators is paramount to the creation of a salient and localizable cue.

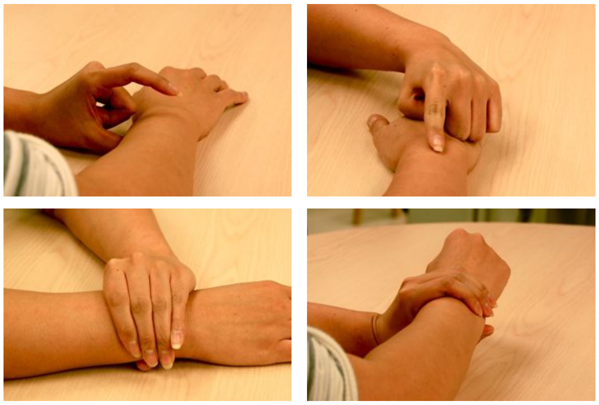

Figure 1: Various forms of human physical contact: tapping, dragging, squeezing, and twisting.

Many possible applications of body-grounded tactile actuators exist, some of which have already been explored in depth by other researchers. Baumann et al. created prototypes of tapping and squeezing actuators that successfully emulated human attention-getting practices in appropriately intrusive manners [3]. These particular tactors use servo motors to rotate a foam contactor into contact with the user's wrist or to contract a strap around the user's wrist. A system of body-grounded tactors has also been used to create a whole-arm tactile display of a virtual or remote environment to facilitate teleoperation of a robotic arm [12]. This system used an array of servomotor-actuated paddles along the length of the arm to indicate contact in the virtual environment. One could also use tactile signals to help position players on a sports field or soldiers on a battlefield, utilizing the privacy of these signals in comparison to auditory or visual cues in order to gain a competitive advantage [1]. Rotational skin stretch represents an additional interesting method for tactile displays [2]. One application of this wearable device would allow an amputee to feel the location or movement of a prosthesis rather than relying on vision alone [14].

The idea of tactile motion guidance may be the most compelling application of body-grounded actuators; a set of tactile cues from a wearable device could help a user learn, relearn, or perfect a vital or complex motion. The tactile interaction for kinesthetic learning (TIKL) system combines a Vicon motion capture system with Tactaid vibrotactile actuators to replace an instructor's tactile guidance for learning new motor skills [10]. While the TIKL system generated noticeable performance gains in hinge joint movements, the researchers noted that the vibrotactile stimulation created little to no improvement in performance in rotational joints, and they suggested further research to find adequate methods of

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*e-mail: astan@seas.upenn.edu
†e-mail: kuchenbe@seas.upenn.edu

feedback on these joints. Another project in our own lab has combined magnetic tracking with vibrotactile feedback in a sleeve aimed at helping stroke patients rehabilitate any upper-body motor skills they may have lost [9]. The user attempts to follow basic arm movements and receives both visual feedback on a monitor and tactile feedback from eccentric mass motors vibrating on specific locations of the arm based on the calculated position error. Vibration and rotational skin stretch have also been used in combination to train walking movements [11].

Ideally, the perception and comprehension of any of these tactile cues would come easily to the user. To this end, cues that are natural or that a user experiences regularly, such as the examples shown in Fig. 1, may hold particular value. Some work has already been done to facilitate tactile interactions like these between humans and humanoid robots, for example allowing a robot to identify and even verbalize the type of physical contact that it receives [7]. An actuator movement based on real physical human contact could also help maintain the sensation of another person being present with an unaccompanied user. For example, the Tap-Tap employs a set of solenoids and vibration motors integrated throughout a wearable scarf-like garment [5]. By recording patterns of humans tapping on momentary switches and activating the solenoids and vibration motors at these recorded intervals, this garment can simulate the presence and touch of a therapist, family member, or loved one. In the broader context of human-computer interfaces, recording and playing back actions that attempt to convey a certain emotion, such as urgency or comfort, could allow easier transmission of human communications in teleconferencing, games, or virtual worlds, e.g., [13]. This goal of creating natural touch sensations inspired our objective of creating a variety of actuators that could play back actual human physical contact, expanding upon Baumann et al.'s work of emulating human attention-getting practices [3].

The next section overviews more traditional approaches to tactile feedback, and Section 3 presents our design paradigm for body-grounded tactile actuators. Sections 4 through 7 detail our tapping, dragging, squeezing, and twisting devices. After a brief evaluation with user comments in Section 8, we conclude and discuss avenues for future work in Section 9.

2 BACKGROUND

Current wearable haptic systems most commonly use vibrotactile stimulation to transmit information to a human. Here we highlight important aspects of this category of tactile actuator, based on the excellent recent review by Jones and Sarter [8]. The human skin has an optimal sensitivity for vibration ranging from 150 to 300 Hz and some sensitivity for vibration from 0.4 to 1000 Hz . Amplitude thresholds at 200 Hertz range from 0.7 microns on the fingertips to 14 microns in the abdominal region, making it relatively easy to mechanically create perceptible tactile stimuli at this frequency. To communicate information via vibration, one can create both spatial and temporal patterns based on the varying durations of sequential vibrations in different motors, with increased duration correlating with increased perceptibility up to bursts of 500 ms. The most common vibrotactile actuators in use are eccentric mass motors and voice coil actuators. Both shafted and shaftless eccentric mass motors rotate an offset mass to create vibrations at a frequency that is coupled with the magnitude, while voice-coil-based tactors such as C2s and Tactaids are typically operated at a single frequency near 200 Hz. A variety of characteristics account for the popularity of these devices, including their relatively low cost, small size, ease of mounting, and high perceptibility.

Despite the widespread use of vibration as a haptic cue in everything from cell phones to video game controllers, it has a variety of limitations that inspire research into alternative sensations. The mechanoreceptors that detect vibrations have large receptive fields, and the vibrations themselves tend to propagate through the region of skin surrounding the actuator. Thus, tactors need to be spaced far from one another for a user to be able to identify which tactor is vibrating. The localizability of these tactors can be improved by placing them near natural reference points like the elbow, wrist, or navel. Furthermore, a change in vibration intensity could affect the human perception of both amplitude and frequency, limiting the effectiveness of varying either as a means of communication.

Another potential disadvantage of the use of vibration as a tactile signal results from the fact that sustained high-frequency vibration is not a phenomenon commonly encountered in the natural world. Sustained single frequency vibration cues can thus feel artificial and annoying. In addition, a masking effect may occur in which a stimulus might not be perceived due to the introduction of another stimulus immediately preceding or following it or at a different location. While vibrations continue to play an important role in tactile feedback systems, these factors encouraged us to seek other methods of communicating information to a human via the skin.

3 PARADIGM

This project aspired to explore a variety of ways to stimulate the human sense of touch beyond the traditional vibrotactile approach. We aimed to create devices that can deliver detectable sensations without overly compromising the characteristics that have made high frequency vibration such a universal form of tactile feedback. By approaching the topic of tactile feedback with an open mind, we also sought to find ways to improve on some of the shortcomings of vibrotactile feedback, including poor localization and artificiality. Our approach entailed building actuator modules that are lightweight, comfortable to wear, reliable, inexpensive, and do not interfere with basic movements. We wanted the sensations they create to be pain-free, localizable, quickly varying, and to cause a fast temporal response from the user.

We hoped to create signals that could vary in both intensity and frequency without the grading of one affecting the perception of the other. Inspired by the application of tactile motion guidance, we preferred signals that had a direction that would be easy for the user to interpret and that would cause a natural movement response of a body part such as an arm or a leg. These factors led us to focus on mechanical stimulation that could be felt on hairy skin rather than the fingertips. Furthermore, we did not pursue thermal or electrocutaneous stimulation because we were concerned about the naturalness and safety of these cues. Thermal stimulation has the added drawback of a low temporal bandwidth.

To facilitate fast prototyping and keep costs low, we chose to design all of our tactile actuators around the Futaba S3114 Micro Servo. Its favorable characteristics include its small mass of 7.8 g, small size of 5.59 cm^3, low cost of fifteen US dollars, and high strength with a maximum torque output of 0.167 Nm. This servo has a maximum velocity of 600 °/s when powered at 6.0 V. As this servo operates in position tracking mode based on a 50 Hz pulse-width modulation signal, its target position can be updated every twenty milliseconds, which is fast compared to human motion output capabilities but slow compared to the high-frequency vibrotactile sensitivity described above.

The auditory noise from these actuators is one of their main disadvantages when compared to vibration motors. While the physical contact of an end-effector against the user's skin does not produce much noise, the servos themselves do, as also noted by [3]. The noise of the servos varies with their speed and torque, occasionally creating auditory cues that are more salient than the haptic cues. This issue could most likely be resolved in future versions by using higher quality DC motors or by adding sound dampening material around the servos.

We controlled these servos using a Phidget Advanced Servo 8-Motor USB board with a Matlab interface. By sending the servo a new position command incrementally every twenty milliseconds, we achieved relatively smooth, highly controllable motions over longer intervals. Furthermore, this servo controller includes a function to read the current it supplies to the servo at any given time, allowing us to write calibration scripts for some of the actuators so they could better fit a variety of users. A sudden increase in current indicates that the servo is encountering resistance and therefore has probably either just come into contact with the user's skin or reached its maximum position. One should note, though, that the provided servo current readings are unitless and noisy. We also used a Phidget 8/8/8 Interface Kit with eight analog inputs, eight digital inputs, and eight digital outputs, allowing us to record voltages from a variety of potentiometers and force sensing resistors in Matlab. By combining the capabilities of these two Phidget boards, we could monitor the analog inputs during the twenty millisecond periods between each servo update, allowing real-time responses in the servo movement trajectories based upon these readings.

With this infrastructure in place, we created four distinct tactile actuators with a versatile set of functions. Our design process included significant efforts in informal user testing and iterative design. While these actuators can all be controlled to track hand-programmed trajectories, we wanted them to be easy for lay people to test out so that we could start exploring some of our envisioned applications. Thus, for each one we also designed a unique movement control interface to allow the playback of actual human motion as a tactile sensation.

4 TAPPER

The first actuator we designed was the tapper, as shown in Fig. 2. It consists of two crank-slider linkages, one attached to each end of the white plastic piece that interfaces with the motor shaft, also known as the servo horn. The two pointed pistons move up and down in their cylinders to make contact with the user's skin. The acrylic linkage elements were manufactured on a Universal Laser Systems laser cutter. All other custom parts for our actuators were designed using SolidWorks and printed in ABS plastic on a Dimension Elite 3D Printer. The servo attaches to the mounting piece via press fit and was further secured with magnet wire. We make these attachments with twisted magnet wire rather than more typical fasteners because magnet wire can hold parts together where screws either would not fit or would not be readily accessible. Magnet wire is also inexpensive and can hold its form under large loads despite being very malleable. An elastic strap holds the mounting piece onto the user's wrist.

The resulting one-degree-of-freedom (one-DOF) system allows equal and opposite linear motion of the two pistons through the rotation of the servo horn. The pistons come into and out of contact with the user's skin with varying intensity. The two contact locations are separated by 30.5 mm. A calibration script allows the system to find an appropriate maximum amplitude for each side of the tapper to accommodate different wrist shapes. When run, the script commands the servo to move back and forth from its starting position to positions at incrementally increasing amplitudes. The servo holds its position for 1 second at each of the amplitudes while measuring the required current at a rate of 50 Hz. If the average value of these fifty current readings is above an empirically tuned threshold, and if a high enough percentage of these readings surpass a separate threshold, then the script records that amplitude as the maximum. The script then repeats for the other piston due to the asymmetry of the human wrist. A sample plot of servo positions and current readings from one of these calibrations is shown in Fig. 3.

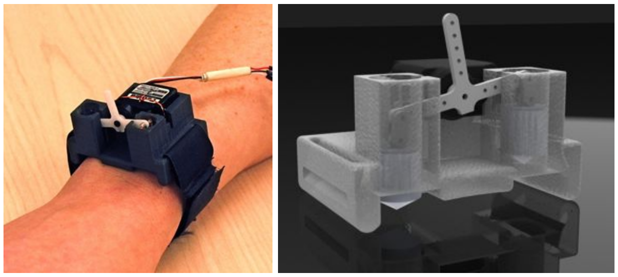

Figure 2: Left: The tapper on a user's wrist. Right: A SolidWorks rendering showing the mechanism by which it functions.

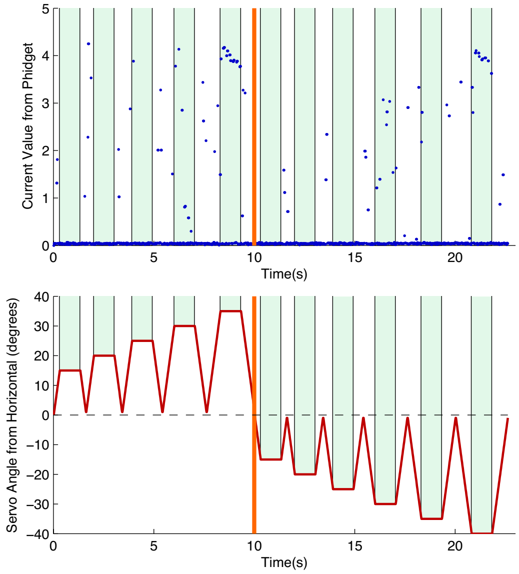

Figure 3: Current readings at each servo position during a sample calibration of the tapper. Positive and negative servo positions indicate tapping with the left and right pistons, respectively. Regions shaded green indicate holding positions.

We used a camera-based motion capture system to measure and play back human physical contact with the tapper. We recorded footage of sample users tapping their finger on their own opposite wrist. To improve visibility, the user wore a black glove with a small white dot on the fingertip in front of a black background. We recorded movies in AMCap with a Sentech STC-C33 USB 2.0 color camera at sixty frames per second (fps). The movies were analyzed frame by frame in Matlab using the image processing toolbox to obtain a list of the xy-positions of the white dot's centroid in each frame, as demonstrated in the video that accompanies this paper.

We scaled the y-coordinates of these positions to fit the amplitude range of the tapper in degrees, and we temporally interpolated the data points to fit the 60 fps video to the 50 Hz timing of the servo's motion commands. Our program can then play back the human tapping motions and patterns by commanding the tapper's servo to a new position at each pulse of the PWM signal to match the position of the dot at that time in the movie. With some modifications, our system could even drive the servo in real time by visually analyzing the human tapping motion as it occurs.

5 DRAGGER

The second body-grounded tactile actuator we designed is called the dragger and is shown in Fig.4. It was originally designed to simulate someone dragging his or her fingertip across a user's skin, but it can actually do more than drag. This two-DOF system consists of a pair of servos mounted in series. The first servo enables vertical motion of the contacting piece, and the second servo enables horizontal motion. The first servo on its own could provide a single tapping motion. An elastic strap holds a 3D-printed base against the user's wrist, and the first servo press-fits into this piece. The second servo press-fits into a separate 3D-printed part that attaches rigidly to the horn of the first servo, secured with magnet wire. A third 3D-printed piece attaches to the horn of the second

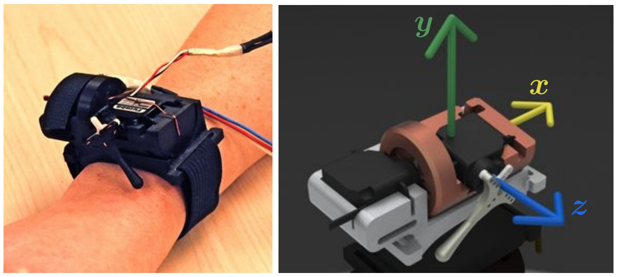

Figure 4: Left: The dragger on a user's wrist. Right: A SolidWorks rendering of its mechanism with coordinate axes.

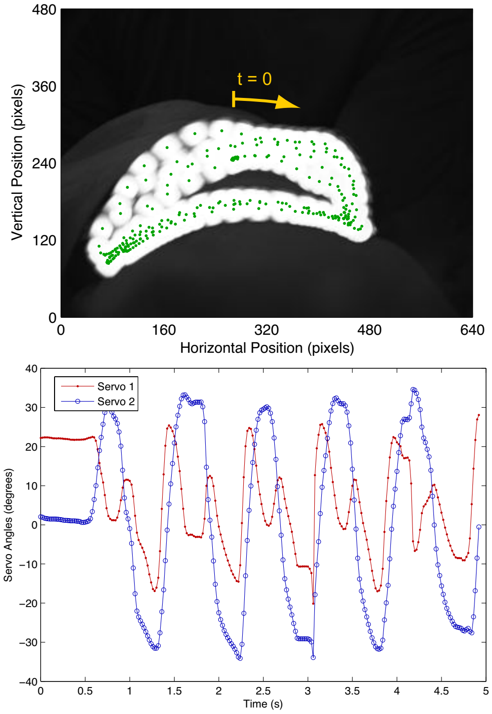

Figure 5: Top: Overlaid frames from a sample video to be played back on the dragger; a green dot marks the centroid of the white dot on the fingertip in each frame. Bottom: a plot of the resulting servo angles from the x-y positions found in the video.

servo and serves to contact the user with its rounded tip.

We mounted the servos with their axes orthogonal to one another, allowing the tip to reach a range of positions in 3D that lie on the surface of an ellipsoid. The coordinate system is centered along the axis of the first servo at the point closest to the axis of the second servo, as shown in Fig. 4. The x-axis coincides with the axis of the first servo, and the z-axis runs parallel to the axis of the second servo in its starting position. The equations that govern the dragger's kinematics in the xy-coordinate plane are as follows:

$$x = l_2 \sin\theta_2 \tag{1}$$

$$y = -l_2 \cos\theta_1 \cos\theta_2 + l_1 \sin(\theta_1 + \phi_{\text{offset}}) \tag{2}$$

The angles θ_1 and θ_2 represent the rotation of the first and second servos, respectively. The lengths $l_1 = 22.9$ mm and $l_2 = 20.4$ mm are the distances in the z and y directions, respectively, from the origin to the center of the contacting tip. The value of ϕ_{offset} is $4.34°$, as a result of the geometry of the design of the dragger, in which the axes of the two servos do not intersect.

To make the path of the dragger tip programmable, we wrote a Matlab script that uses inverse kinematics to calculate the necessary servo angles to place the tip of the dragger at any xy-position within its range. The desired value of θ_2 can be found analytically by solving equation (1) above. Due to its trigonometry, equation (2) does not have a simple analytic solution, so we wrote an iterative algorithm that finds a value for θ_1 that places the tip within 0.25 mm of the desired position.

Figure 6: The master device for real-time control of the dragger.

We used a setup very similar to the one used for the tapper to record and play back human motion on the dragger. For these videos, both of the user's arms were covered in black sleeves and gloves, and the finger with the white dot played out trajectories across the opposite wrist. By scaling and interpolating both the x- and y- positions to fit into the x-coordinate range of the dragger and then moving the y-positions to line up with the user's wrist, we were able to play back trajectories of someone dragging a finger across the user's wrist in either direction and of someone tapping sequentially at multiple points across the wrist, as demonstrated in Fig. 5 and shown in the video that accompanies this paper.

We devised a second method that allows real-time play back of human motion on the dragger. This setup involved a master-slave pairing to control the dragger through teleoperation. We designed and 3D-printed the master device shown in Fig. 6. It has the same geometry as the dragger, but with long-stemmed potentiometers in place of the servos. As one user moves the tip of the master around its workspace, the voltage readings at the wipers of the potentiometers change. These readings are then scaled into corresponding servo angles, which are commanded to the dragger's servos at each pulse of the 50 Hz PWM signal. The dragger tip then moves around its workspace in the same manner that the master tip is moving.

6 SQUEEZER

We continued our exploration of body-grounded tactile actuators by creating a squeezer, shown in Fig. 7. The inspiration to build an actuator that could squeeze the user's wrist stemmed largely from the research of Baumann et al. [3]. Our squeezer functions in a similar manner to theirs: one servo is mounted onto the user's wrist to lengthen and shorten a fixed-length wristband. However, the mechanisms by which the two devices contract the wristband differ greatly. Whereas Baumann et al. designed a wire linkage system to connect each end of the servo horn to either end of the wristband so that both sides contract with the servo rotation, we chose a simpler solution: one end of the strap is fixed to the squeezer's base, and the other end is connected rigidly to the top of the servo horn.

As with the tapper, the servo press-fits into a 3D-printed mounting piece that straps onto the user's wrist. A separate 3D-printed piece connects the servo horn to the other end of the strap. With this mounting technique, the servo has roughly a sixty degree range of motion. To achieve the maximum squeezing force, we focused on locating the strap connection as close to the axis of the servo as possible. Decreasing this distance shortens the moment arm, leading to a larger force per unit of torque from the servo. We made the strap out of a generic hook and loop fastening material. The code behind the functioning of the squeezer is the simplest programming of the four actuators we designed, with the angular position of the servo corresponding directly to the tightening or loosening of the strap for the servo's range of motion.

One of the challenges that arose while designing the squeezer

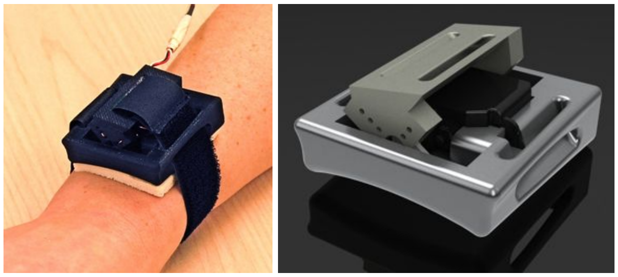

Figure 7: Left: The squeezer attached to a user's wrist. Right: A SolidWorks rendering of its mechanical design.

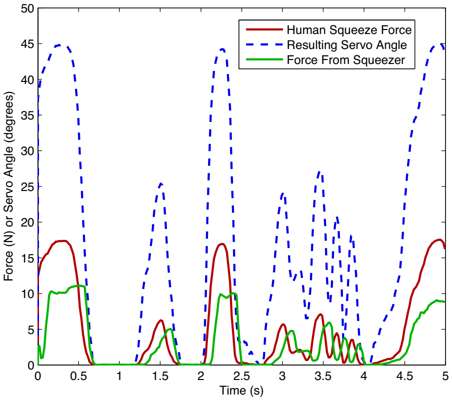

Figure 8: Sample squeezer data from replaying human motion.

was ensuring that the strap fit correctly on a variety of users, so that the servo's range of motion corresponded to the varying degrees of tightness. Ideally, the end of the range of motion would match up with the maximum torque of the servo. To accomplish this, we used a force sensing resistor (FSR) to calibrate the squeezer. This square-shaped FSR is placed between the user's wrist and the strap of the squeezer during the calibration. We created a voltage divider circuit and used an analog input on the Phidget board to measure the voltage across the FSR, which was connected between +5V and a standard 2kΩ resistor to ground. The FSR decreases in resistance with increasing applied force, resulting in an increase in output voltage. We calibrated the FSR using a digital balance.

With this FSR in place, we created a script to calibrate the forces the squeezer applies for any given strap tightness. The servo in the squeezer incrementally tightens the strap through its range of motion, and the script records the force readings through the Phidget. If the force applied at the full squeeze is too low, the user is instructed to tighten the strap by repositioning the hook and loop fastener. Conversely, if the servo reaches its maximum torque too early, indicated by the applied force leveling out at the end of the calibration, the user is instructed to loosen the strap.

We used a second, dot-shaped FSR to record and play back human physical contact on the squeezer. The script that runs the squeezer in Matlab reads this analog input value from this FSR during the twenty-millisecond periods between each position update of the servo. It then scales the value onto the range of motion of servo positions and adjusts the target position accordingly. As a result, the actuator creates a gradable squeeze that follows the human's squeezing motions, strengths, and patterns in real-time. To test the accuracy and gradability of the squeezer, we ran this script to play back human contact while simultaneously monitoring the readings of the square FSR between the squeezer strap and the user's wrist. The video that accompanies this paper shows the squeezer in use, and Fig. 8 shows the readings from the FSR being squeezed, the resulting servo angle in real-time, and the resulting force from the squeezer on the user's wrist.

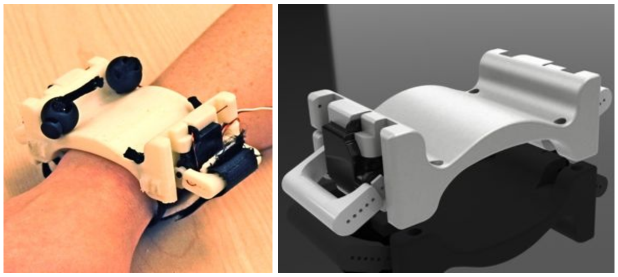

Figure 9: Left: The twister on a user's wrist. Right: A SolidWorks rendering of its mechanical design.

7 TWISTER

The final actuator we built is the twister, as shown in Fig. 9. It stretches the skin on the underside of the user's wrist back and forth with a two-DOF system. Orienting the forearm with the hand palm-down, two thin elastic bands secure the 3D-printed mounting piece onto the top of the wrist, permitting the center strap on the underside of the forearm to stay loose while the user puts on the twister. The two servos press fit into the mounting piece on either side of the wrist, with the servo axes running along the length of the forearm. Our mechanical design allows a range of motion of about 120 degrees for each servo.

In the neutral position, each of the servo horns points outward from the wrist, holding the center strap up against the underside of the user's wrist. The strap fastens around a connection piece on the end of each servo horn. To twist the user's wrist clockwise about the axis of the forearm, both servos rotate clockwise. This moves the strap connection pieces upward on the left side and downward on the right, stretching the skin on the underside of the wrist from right to left. To ensure that the strap does not slide across the user's wrist, a layer of foam that has a high coefficient of friction with skin was sewn into the strap. Since the twister has two degrees of freedom, it also has the capability to tighten or loosen around the user's wrist at any point by rotating both servos upward or downward, respectively.

We created a handle attached to a rotary potentiometer to capture human twisting motions for playback on the twister. The script employed in this task functions in a manner very similar to the script used to play back motion on the squeezer. When wired to the Phidget board, the analog reading from the potentiometer correlates linearly to the angular position of the handle. The script scales this value to fit the range of motion of the twister to play back twisting motions in real time. The video accompanying this paper demonstrates the twister in use.

8 EVALUATION

All four of our wearable tactile actuators were demonstrated to a diverse set of users at the University of Pennsylvania Haptics Laboratory Open House on December 10, 2010, to collect informal evaluations. Approximately fifty individuals tested the devices and provided verbal feedback, and fourteen people provided written comments as well. Most users experienced and compared the tactile sensations from all four devices, but some felt only one or two. Users were prompted to comment on the quality of the prototypes in relation to both their comfort and the sensations they create.

Most users focused on the positive aspects of the actuators in their comments. The tapper was praised for delivering a "strong" sensation and for being "probably the most effective" of the four devices. Multiple users found the dragger to be "very intuitive" and the squeezer to be "very nice." The squeezer received particular praise for its playback of human motion, with "good correlation between how hard I was squeezing and how hard I was being squeezed," and that "this was a very realistic and comfortable device. The sensation is very noticeable and not tight or unpleasant."

For the twister, users found that the “movement on this device is more subtle but still noticeable and natural considering its intention,” and that it “really grabs my skin and twists.” With the playback of human twisting, users “could really tell which direction the handle was turning based on the twisting.”

A few users offered criticism and design suggestions for the actuators, sometimes for the same qualities that other users had praised. Some felt that the tapper was not easy to understand and needed to be stronger, and some mentioned that the direction of the dragger was not intuitive to them. Others said that the squeezer “could use higher pressure,” and that the twister “sensation was weak, [and] didn’t provide [a] strong impression of the twisting action.” One user suggested replacing the plastic tip on the dragger “with something more soft [because it is] harsh on your skin.” Users provided contrasting opinions regarding which side of the wrist would provide clearer sensations for the various forms of tactile feedback.

Some comments also proposed a wide range of possible applications for the tactile actuators, including using the tapper in a video game or using the dragger and squeezer in conjunction with online video conferencing to simulate human touch. One user suggested the devices were promising for motion guidance, stating that the tapper would be a “great tool to facilitate supination of the forearm,” that the dragger provided “nice feedback for reciprocal forearm rotation,” and that the twister would be a “good way to increase forearm pronation.” Another user proposed that the dragger could be used “in respiratory therapy to help pace breathing rate,” drawing from experience using a similar dragging motion across the wrist of a recovering heart attack patient in the hospital.

9 CONCLUSIONS AND FUTURE WORK

The iterative design, prototyping, and testing of our tactile actuators has further proven the feasibility of creating tactile sensations beyond the common, established vibrotactile stimulation. Our four actuators maintain many of the advantages of vibration for use as a signal while also improving upon some of its shortcomings, as discussed below. Though further improvements are necessary, all of these actuators are relatively small, inexpensive, non-intrusive, and localizable. In addition, all of the sensations these actuators produce are gradable in magnitude and can be activated in a variety of temporal patterns. While vibration motors and voice-coil actuators have only varying degrees of intensity, the tapper, dragger, and twister produce signals that also have an associated direction, a trait which could be particularly useful for certain applications, such as motion guidance. In addition, the signals produced by these actuators do not seem to propagate throughout an entire region of the user’s skin as vibration does.

The sensations created by each of these actuators also seem to feel more natural than vibration. While the high-frequency vibrations typically created by eccentric mass motors and voice coil actuators are rarely encountered in any other situation, tapping, dragging, squeezing, and twisting all represent sensations that humans experience on a regular basis, even in a world without technology. By playing back actual human physical contact on each of these actuators, we have created a set of tactile user experiences that one could not replicate with vibration.

Along with the noise disadvantages discussed in Section 3, maintaining the correct form fit for a variety of users throughout a variety of physical motions remains another challenge for the further development and successful implementation of these actuators. We noticed that for many users, simply turning or bending the wrist disrupts the calibration of and sensation from an actuator. Building actuators to play these sensations on other parts of the body would require further design and prototyping, and it could potentially further interfere with basic user motions.

Looking forward, we hope that these sensations will prove effective in a variety of motion guidance applications, from stroke patients rehabilitating their motor skills to athletes refining their form for a golf swing or weight room exercise. To this effect, we plan to run a human subject study to compare the effectiveness of these devices against vibration cues during motion guidance. Finally, we hope that other valuable applications for these types of tactile sensations and playback of human physical contact will arise as technology continues to progress.

ACKNOWLEDGEMENTS

The authors thank Karlin Bark for her guidance on designing skin-stretch actuators as well as her help with the photos and videos for this paper. This material is based upon work supported by the National Science Foundation under grant 0915560.

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