Design of a Fingertip-Mounted Tactile Display with Tangential Skin Displacement Feedback

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Abstract—Application of tangential skin displacement at the fingertip has been shown to be effective in communicating direction and has potential for several applications. We have developed a portable, fingertip-mounted tactile display capable of displacing and stretching the skin of the fingerpad, using a 7 mm hemispherical tactor. In vivo tests of fingerpad skin stiffness were performed to determine the forces required to effectively render stimuli. Other design parameters such as stimulus speed and displacement were derived from our earlier work. The tactile display is capable of rendering ±1 mm of displacement at arbitrary orientations within a plane and with rates of approximately 5 mm/s. Compliance and backlash in the device's drive train were characterized using external measurements, and were compensated for in software to reduce the impact on device hysteresis.

Index Terms—Haptic device design, haptic I/O, lateral skin stretch, tangential skin displacement, tactile display.

✦

1 INTRODUCTION

HUMANS are highly sensitive to tangential skin displacement at the fingertip and there is great potential for using this stimulus in diverse applications. A variety of users, ranging from a driver on unfamiliar roads to a soldier in an urban setting, could benefit from haptic navigation cues, shown schematically in Fig. 1. Haptic cues have the advantage of leaving the user's eyes and ears free for safety-critical situation awareness. In this paper, we present a haptic direction display with potential for integration into portable, handheld devices.

Our previous research has suggested that tangential skin displacement, inducing shear forces and lateral skin stretch at the fingertip, is an effective means of communicating navigational cues [1]. In another potential application, a directional display could be integrated into a computer interface, e.g., a laptop TrackPoint mouse interface, to direct a user's attention to important on-screen information or for use as an all-purpose input/output device. Early work by Gould et al. suggests tangential skin displacement as an ideal means for direction communication, having greater perceptibility than stimuli which slip along the skin, moving normal forces, and pin arrays [2]. More recent findings by Norrsell and Olausson, among others, agree that humans are more sensitive to directional skin stretch than to other tactile directional cues such as skin slip [3]. Several researchers, including Drewing et al. [4], Keyson and Houtsma [5], Placencia et al. [6], and Vitello et al. [7] have sought to characterize thresholds of direction discrimination of lateral skin stretch at the fingertip. While these researchers disagree in their specific findings, their data all suggest that skin stretch could be used for communication of navigational and directional cuing information. Additionally, medical research has found skin stretch

at the fingertip to be a useful aid for disabled patients to better control posture and balance (Wasling et al. [8] and Dickstein et al. [9]). All of these applications would require a small, portable display, which we have developed and describe in this paper.

A few fingertip-based devices, capable of rendering tactile direction information, have been previously developed. Zhou and Miyaoka used a 2D linear motor developed by Fuji Xerox to impart skin stretch in a Braille-like mouse interface. This device is well suited as a desktop computer interface but is not practical for many mobile applications due to the large footprint and high power demands of the linear motor [10]. Webster et al. developed a small powered trackball-type device, mounted to the end of Phantom haptic device, to render both skin stretch and slip [11]. The trackball-type design is capable of imparting very long slip sensations, but the production of slip is not necessary for our applications. Tsagarakis et al. developed a wearable, fingertip-mounted slip display using two conical rollers, but like the Webster et al. device, this device was designed to render continuous slip sensations rather than directional skin stretch [12]. As we did not seek to render slip, we designed a compact device capable of displacing the skin to render shear forces and lateral skin stretch only.

Other researchers have used wearable devices to communicate direction. Direction cues have been effectively rendered using arrays of vibrating motors, as was done by Van Erp, who placed vibrators on a wearable belt [13]. Vibrotactile stimulation, however, is not suitable for integration into small devices, as vibrators typically require large spatial separation in order to be discernable. Another wearable device was developed by Bark et al. to rotationally stretch the skin of the forearm as a substitute for proprioceptive feedback [14]. While wearable devices have been shown to be effective, we sought instead to develop a device with potential for integration into handheld devices.

2 DESIGN REQUIREMENTS AND FINGERPAD CHARACTERIZATION

In previous experiments, we characterized important factors for the communication of direction through tangential skin displacement at the fingertip [1]. These experiments were conducted with a large bench-top device, but their results have established the design parameters for our fingertip-mounted device. In these prior experiments, we found that stimulus speed and displacement are both important, with larger displacements and faster speeds resulting in greater communication accuracy (see Fig. 2). From these experiments, we concluded that speeds of 2 mm/s and displacements of 0.2 mm were sufficient to communicate direction with high accuracy. However, in an application where the user's attention is shared with other tasks, we would expect lower accuracy rates. We, therefore, set design requirements to achieve 99+ percent communication accuracy for our fingertip-mounted display, specifying minimum device displacement and speed requirements of 0.5 mm and 2 mm/s, respectively.

To choose appropriate actuators for our device, it was necessary to characterize the stiffness of the fingerpad and to understand the forces that would be required for the application of the specified displacement. Wang and Hayward have performed in vivo measurements of fingerpad load-displacement behavior, using ~1 mm instrumented tweezers [15]. However, we require data more specific to our device. That is, we need information about the interaction between the skin and our specific (7 mm) tactor, in our required range of speeds and displacements. To provide this data, a series of in vivo measurements were taken to characterize the interaction between our device and the skin.

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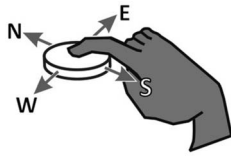- S.K. Horschel is with Applied Research Associates, Randolph, VT. E-mail: shorschel@gmail.com.

Fig. 1. Communication of direction through tangential skin displacement at the fingertip.

Volunteer subjects were recruited for a series of skin force measurements. Six unpaid subjects were tested, four male, two female, ranging in age from 21 to 36 years. Five of the subjects were right hand dominant and one was left-hand dominant. The right index finger of each subject was restrained with a splint and foam pads at the middle phalanx. The distal fingerpad was brought into contact with the tactor used in our finger-mounted device ($\sim$7 mm textured rubber ThinkPad TrackPoint tactor). The tactor was mounted to a custom-built 3-axis force sensor that was attached to a bench-top, 2 degree-of-freedom, lead-screw-driven stage. Both the stage and the force sensor are described in [16]. The stage was driven 2 mm in four orthogonal directions (distal, proximal, radial, and ulnar) at 4 mm/s under computer control. During each movement, the forces between the finger and the tactor were recorded, using a Sensoray 626 data acquisition card at 1 kHz. The custom force sensor had a range of ±14 N and sensitivity of $\sim$0.8 mN/bit. To best simulate realistic use of the device, subjects were permitted to apply a normal force that felt comfortable and that was sufficient to prevent macroscopic slip between the finger and the tactor. Applied normal forces were between 0.5 and 1.5 N. As discussed in our earlier work [1], we expect that some micro-slip occurred between the tactor and the skin, particularly around the edges of the tactor. The experiment was conducted with approval of the University of Utah Institutional Review Board.

At the speed and displacement used in this experiment, the force-displacement relationship was observed to be nearly linear. After discarding those data affected by acceleration transients at the start of each movement, a line was fit to the remaining data, the slope of which is the measured linear stiffness of the skin. Data measured in the distal direction, along with fit lines, are shown for all six subjects in Fig. 3. These data are characteristic of all four directions. The range of measured stiffness in all four directions is tabulated in Table 1. Cardinal directions shown in the table correspond to those in Fig. 1

Our measurements indicate a large variation in fingerpad stiffness between subjects, possibly due, in part, to variations in applied normal force. This variation is in agreement with the

Fig. 3: Force-displacement curves and fit lines for the interaction between the 7 mm tactor and fingerpad. A large range of fingerpad stiffnesses are observed, but all curves are nearly linear. This plot shows measured force-displacement behavior in the distal direction. Results are tabulated in Table 1 for all four orthogonal directions (distal, proximal, radial and ulnar).

observations of Wang and Hayward [15]. For some subjects, the fingerpad is quite stiff, approaching 4 N/mm in the distal direction. Thus, if we hope to render displacement of 0.5 mm or greater for all users, we will require actuators with an output force of at least 2 N.

3   DEVICE DESIGN

Various design concepts were considered and prototyped, but a device driven by radio-controlled (RC) hobby servos was found to best deliver the high forces that were suggested by our finger stiffness characterization experiments. The fingertip-mounted directional display is built around two servo motors manufactured for the radio-controlled hobby market (Cirrus CS101 Micro Servo; specified torque 98 mN·m). Fig. 4 shows a photograph of the completed device. An exploded view of the device is depicted in Fig. 5, along with the device reference frame. The assembled device has a mass of 39 g. For more detail, see [17].

The device uses two RC servos and a compliant flexure stage to create planar motion. The servos can operate simultaneously, allowing motion along any path in a plane. Pins protrude upward from each RC servo output arm into orthogonal slots in the flexure. The flexure is designed such that rotation of a single RC servo induces motion on a single axis. Slots in the flexure stage allow the transmission pins to move freely when the opposite servo is actuated, thus decoupling the motions of the two servos. This flexure also serves to decouple the tactor from the small vibrations of the servo gears. The calculated force of the servos on the tactor is 25.1 N, well in excess of the 2 N requirement. The device is capable of rendering displacements greater than ±1 mm on each axis.

The device interacts with the fingerpad through a shear tactor, as seen in Fig. 5. The tactor is a textured rubber ThinkPad TrackPoint interface 7 mm in diameter. This tactor was chosen based on pilot experiments conducted during our earlier research [1]. The fine-scale texture on this TrackPoint tactor accentuates

Speed (mm/sec)

		0.5	1	2	4
Displacement (mm)	1	0.98 ±0.024	0.99 ±0.011	1.00 ±0.000	1.00 ±0.009
	0.5	0.95 ±0.024	0.98 ±0.013	0.99 ±0.010	0.99 ±0.009
	0.2	0.85 ±0.067	0.94 ±0.050	0.96 ±0.025	0.95 ±0.027
	0.1	0.69 ±0.083	0.85 ±0.061	0.90 ±0.027	0.89 ±0.027
	0.05	0.54 ±0.086	0.72 ±0.069	0.73 ±0.061	0.79 ±0.046

Fig. 2. Results of previous direction identification experiments. Each cell shows the accuracy rate and corresponding 95 percent confidence interval for a range of stimulus displacements and speeds. Cell shading corresponds to accuracy rates. These results are used as design guidelines for our portable tactile display.
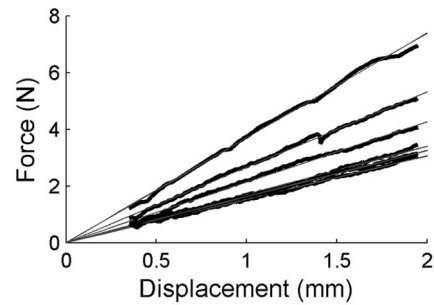
TABLE 1
Lateral Fingerpad Stiffness in Four Directions

(N/mm)	Proximal (S)	Distal (N)	Radial (W)	Ulnar (E)
min	0.89	1.53	0.87	0.79
mean	1.58	2.22	1.37	1.18
max	2.49	3.69	1.94	1.84
std. dev.	0.66	0.83	0.40	0.37
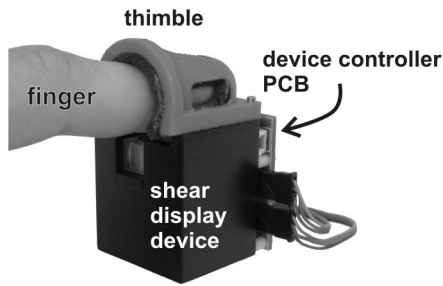
Fig. 4. Photo of tactile display with printed circuit board (PCB) control electronics.

Fig. 5. Exploded assembly view of tactile display, along with device reference frame.

applied direction sensations, has high friction to prevent slip, and is widely available.

3.1 Flexure Design

The flexure stage was molded from two different urethanes: one soft urethane (90A shore hardness, IE-90A from Innovative Polymers) and one hard urethane (80D shore hardness IE-80D from Innovative Polymers). The harder urethane formed the main structure of the device while the softer urethane was used to make flexible joints (Fig. 6). The flexure was manufactured through sequential machining and casting operations, using Shape Deposition Manufacturing (SDM). SDM uses wax tooling blocks and a CNC milling machine to create molds into which urethane polymers are cast and subsequently machined [18].

To reduce bending compliance between the servo arms and the slots of the SDM flexure, a press-fit tube was bonded to the base of the transmission pins, thus improving the cantilever stiffness between the transmission pins and the servo arms. Additionally, a brace plate was placed below the flexure stage to prevent the stage from deforming downward out-of-plane due to applied finger pressure on the tactor.

3.2 Device Electronics and Control

The control of the device is accomplished by using a microcontroller (MCU) and custom electronics. The rotational position of the servos is controlled by sending a 50 Hz Pulse-Width-Modulated (PWM) signal to each servo. Output positions of 0 to 180° are commanded by varying the pulse from approximately 1 to 2 msec in length. The PWM signal is generated by a dsPIC30F2012 MCU programmed to accept input commands from a variety of sources.

A printed circuit board (PCB) was fabricated to facilitate interaction between the user and the display device. The PCB accepts three different control inputs: analog inputs from a 2-DOF analog joystick, parallel digital inputs from a push-button controller, and asynchronous serial (RS-232) inputs. Wired and wireless remote controls with push buttons were developed to communicate repeatable signals to the user. The remote control features four direction buttons and can automatically generate repeated stimuli (outbound motion then return to center, ~1x per 2 sec), using timing features programmed on the device MCU. An RS-232 serial communication input to the device enables the display to be controlled by a PC, which is useful for conducting structured experiments.

Power requirements vary with usage, but the device has been found to run for approximately 2 hours of near-continuous use on four 1,000 mA·h AAA batteries. This battery life is sufficient for our experimental goals.

4 DEVICE CHARACTERIZATION AND PERFORMANCE

Device backlash, movement speed, and repeatability were characterized through empirical testing. The display was found
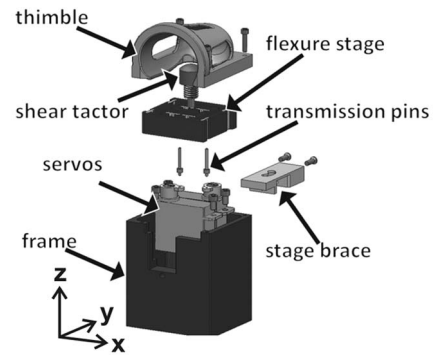
to exhibit significant hysteresis, but much of this was corrected for in the control software. The varying properties of different user's fingers affected the rendered stimulus distances, but stimuli were still highly repeatable for any given subject. Because stimuli were rendered at levels that can be easily perceived by subjects, all uncorrected stimulus errors were small enough to permit the use of the device in experiments with both between-subjects and within-subjects experiment designs.

4.1 Characterization Methods

Two different characterization methods were employed: one to gather position data and the other for velocity data. Position was measured by placing the tactile display in a vise and affixing the probe of a dial indicator to the tactor just below where the tactor contacts the finger. Care was taken to assure that the probe did not interfere with the finger or the flexure stage. The bias-spring was removed from the dial indicator so that the indicator did not apply any appreciable force to the test device. All characterization was done with a finger in the device's thimble and pressing down on the tactor. The characterization process was completed independently for the two axes of the device.

For velocity and motion profile measurement, data were acquired using an infrared range sensor, as described by Gleeson and Provancher [19] with a Kodak 18 percent gray card attached to the tactor. The tactile display was moved along its entire travel in orthogonal directions and the motion profile was recorded. A line was fit to the data to determine the average velocity of the tactor. These measurements were repeated 20 times in each direction and the results were averaged. This procedure was completed with the device both loaded and unloaded. These tests used a block of foam
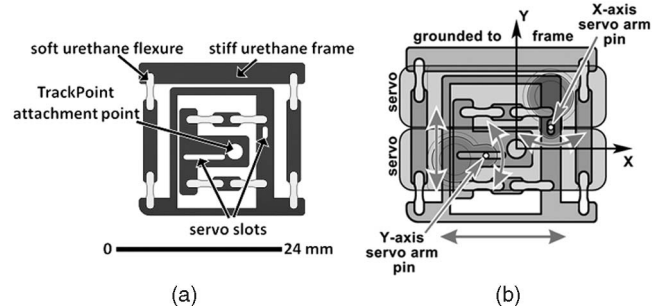

Fig. 6. (a) The SDM flexure stage is comprised of two different materials, stiff urethane for the main support frame and soft urethane for the flexible connections. The slots in the flexure stage allow the pins to couple motions of each servo to only a single axis of motion and prevents the mechanism from becoming over constrained. The flexure is 7 mm thick. (b) Translucent view (without device frame) showing how the pins on the servo output arms couple with slots in the flexure stage.
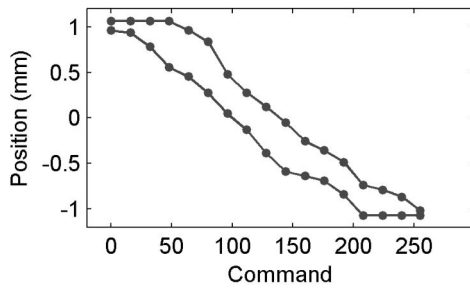
Fig. 7. A single hysteresis loop for y-axis tactor motion of the tactile display. Position is shown as a function of the input command. Input commands to the device's RC Servos were PWM signals encoding positions with 8-bit resolution (0-255 corresponding to 1-2 msec pulses). The effects of backlash and compliance can be seen at both ends of the curve.

rubber as a simulated finger load, providing isotropic resistance and a constant normal force (approximately 1 N). The stiffness of the foam rubber was measured to be 1.6 N/mm, which is within the range of measured fingerpad stiffness. A real finger could not be used during velocity measurements because of the difficulty of maintaining constant normal force on the moving tactor.

4.2 Hysteresis

A simple test was conducted to characterize device hysteresis. Each axis was moved along its entire travel, in both directions, while position data were recorded. This was repeated four times for each axis. A representative hysteresis curve for the y-axis is shown in Fig. 7. The x-axis exhibits similar characteristics. The effects of hysteresis were repeatable and showed strong effects of backlash and compliance at both ends of travel. Knowledge of this behavior informed how stimuli were tuned.

4.3 Tactor Motion Profile

The loaded and unloaded motion profiles of the tactor were observed to be approximately linear. A typical motion profile is shown in Fig. 8. The average velocities of the tactile display, unloaded and loaded, were 8.7 mm/s and 5.6 mm/s, respectively. The velocity was observed to vary as a function of direction, varying as much as 2.2 mm/s slower than the mean. These variations cannot be explained by device construction or mechanism geometry, but could be an effect of anisotropy in the internal servo position control or could be due to manufacturing variances in the servos. However, since the slowest observed velocity (3.4 mm/s) is well above our design specification of 2 mm/s, these variations are not a concern. Additionally, it was observed in Gleeson et al. that subject performance was largely insensitive to changes in stimulus velocity, for all velocities above 1 mm/s (Fig. 2) [1].

4.4 Stimulus Tuning

Using the information obtained from the hysteresis curves, a control method was developed and tuned to help correct for compliance and backlash. The device was capable of rendering motions up to ± 2 mm but due to compliance in the system, this was reduced to approximately ± 1 mm when loaded. Seeking to render stimuli as clearly as possible, the displacement and repeatability of the rendered stimuli were maximized. To account for backlash, state-dependent commands were empirically determined for stimuli in four orthogonal directions. A controller was implemented in software that recorded past movements, predicted the backlash state, and issued the appropriate commands.

4.5 Mechanical Performance Verification

Participants were recruited with a variety of finger sizes and tested to verify the performance of the device. Six male subjects were
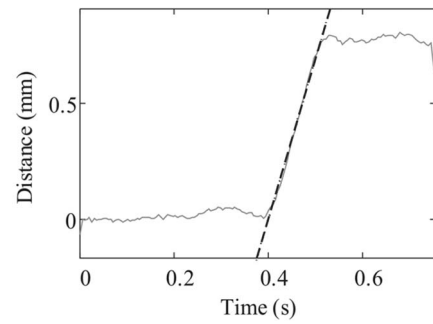

Fig. 8. Motion profile for the loaded tactile display with fit line.

tested, aged 21-36 years. Each test consisted of 10 movements, going from center, to positive displacement, back to center, and to negative displacement. This was repeated on both axes. At each location, the position of the tactor was measured with the modified dial indicator.

Device performance varied between subjects, but was quite constant for each individual subject. The controller did not compensate perfectly for hysteresis with all subjects, due to the varying stiffness of subjects' fingerpads. See Fig. 9 for a simplified schematic illustration of the device-finger interaction. The motor applies force, and position, x_1, is measured internal to the servo. The resultant position of the tactor, x_2, depends on k_1, the stiffness of the flexure, and x_2, the stiffness of the fingerpad. The stiffness of the flexure is constant, but the stiffness of the fingerpad is variable between subjects. With k_2 unknown, it is not possible to precisely control the position of the tactor, x_2, without individual calibration. This is a limitation of the device design, but an acceptable one, as will be shown.

The consequence of the variable fingertip stiffness is that hysteresis could not be entirely eliminated for all subjects. Thus, some uncorrectable error in rendered stimulus displacement remained. The average lengths of the rendered stimuli on each axis, along with RMS error are 1.10 ± 0.10 mm and 0.99 ± 0.10 mm for the X- and Y-axes, respectively. This remaining position error was found to be negligibly small. Before the implementation of state-dependent hysteresis correction, position errors exceeded 0.5 mm.

While the actual length of the rendered stimuli varied between subjects, stimuli varied little for each individual subject, as measured by the distribution of rendered stimuli. The average within-subjects standard deviation of rendered stimulus distances was around 0.05 mm.

4.6 Device Validation Perceptual Experiment

The ability of the device to effectively communicate direction was confirmed in a short user study. Participants wore the portable shear display on their right index finger and were asked to identify the direction of 32 randomly ordered stimuli. Responses were entered using the arrow keys of a computer keyboard. This validation study was conducted as part of a larger experiment, and due to the nature of that experiment, stimuli were only presented in two directions: left and right. The experiment was conducted on
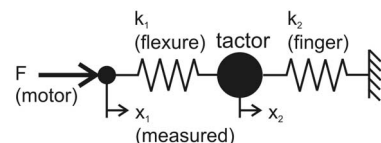

Fig. 9. A simplified schematic of device-finger interaction. With the stiffness k_2 variable between subjects, it is not possible to precisely control the position of the tactor, x_2, without tuning the device for each user.

10 subjects, five female, all right handed and ranging in age from 20 to 26 years (average age 23 years). Subjects were compensated for their time. The experiment was conducted with the approval of the Purdue University Institutional Review Board.

All subjects correctly identified the direction of 100 percent of the stimuli. Because rendering errors are similarly small on both axes (Section 4.5) and because users perceive the stimuli equally well on both axes [1], the results of this study can be generalized to stimuli in the proximal-distal direction. Although this experiment was conducted using only two directions, the error-free subject performance strongly supports the use of this device for effective tactile direction communication.

4.7 Discussion

Because fingerpad stiffness varies between users, the device did not perform exactly the same for all subjects. The error resulting from fingerpad stiffness variability, however, is negligible. Our previous direction identification experiments characterized identification accuracy over a range of stimulus speeds and displacements (Fig. 2). For the speed at which the miniature shear display operates, 5.6 mm/s, these experiments found accuracies of $99+$ percent for displacements larger than 0.5 mm. Because all stimuli rendered by the miniature shear display are approximately 1 mm, we can be certain that direction will be accurately communicated. This conclusion is supported by the results of a human-subjects direction identification experiment.

5 Conclusions and Future Work

We have designed, built, and tested a fingertip-mounted tactile device to render tangential skin displacement at the fingertip. Device design parameters were derived from earlier research and in vivo measurements of fingerpad stiffness. A compliant flexure stage is used to transform the rotation of two RC hobby servos into planar, translational motions. The compliance of the flexure, along with backlash in the servo gears, results in significant device hysteresis. This hysteresis is largely corrected in control software, but the variation in fingerpad stiffness between subjects resulted in some uncorrectable error. Results from earlier research and validation tests on human subjects show that remaining error is unimportant. In the future, our portable device will enable us to conduct application experiments with mobile subjects receiving navigation cues at their fingertip. We will also investigate complicating factors, such as how direction information is perceived when the position and orientation of the user's finger changes. Further device refinements and miniaturization are being considered.

ACKNOWLEDGMENTS

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