Ungrounded Multi-Fingertip Tactile Device for Improved Typing Performance in Virtual Reality

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Abstract— **This work presents a novel ungrounded multi-fingertip tactile device for use in virtual environments. The device combines 1 degree of freedom skin deformation with high fidelity vibrotactile cues in a form factor significantly smaller and lighter than existing fingertip devices. We specifically examine the effects of using three of these fingertip haptic devices in various feedback modes for the task of multi-finger typing on a virtual ungrounded keyboard. We show that the addition of haptics significantly improves typing performance, with the largest improvement coming from conditions including normal force feedback. This study demonstrates that fingertip skin deformation combined with high fidelity vibrotactile cues can provide a compelling haptic experience appropriate for virtual reality tasks involving fine motor movement of multiple fingers.**

I. Introduction

Recent advances in display and graphics technologies have brought virtual reality (VR) and augmented reality (AR) closer to the mainstream. However, the user interfaces and input devices of VR/AR remain relatively crude. All currently available headsets are limited to game controllers with physical buttons and basic vibrational actuators (Oculus Touch, HTC Vive) or a limited amount of hand tracking and gesture recognition (Microsoft HoloLens). Even when full hand tracking is available through external add-ons like Leap Motion, the lack of haptic feedback can make even simple tasks like button selection and typing difficult, resulting in a frustrating experience for users.

The goal of this research is to develop a lightweight, highly wearable ungrounded fingertip device that can provide 1 degree of freedom (DoF) force feedback and high-fidelity vibrotactile feedback (Fig. 1). Major design goals included an order of magnitude weight reduction relative to existing devices, and full compatibility with external tracking solutions that allow multi-finger tracking with no added sensors on the fingertip device itself. Because the device is ungrounded and tracking is provided by a headset-mounted device, this solution vastly expands the possible workspace for haptic interactions. A 1 DoF skin deformation actuator was chosen because previous research has suggested that higher levels of haptic accuracy may not be necessary for compelling VR experiences and improved task performance [1]. A piezoelectric actuator was chosen because it can display a wider range of frequencies and amplitudes than a traditional ERM or LRA, and does not have the spin-up time associated with those devices. This allows the rendering of fast transient and wide frequency bandwidth tactile cues.

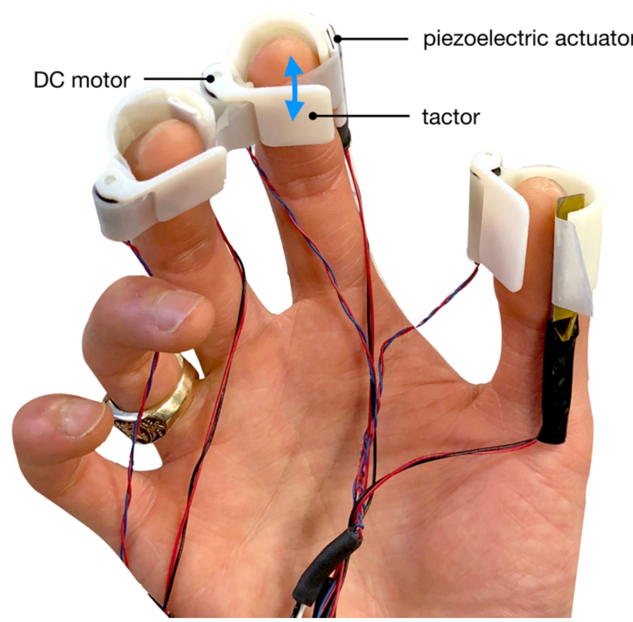

Figure 1. Image of device being worn on thumb, index, and middle finger. The low-profile device provides one-degree-of-freedom normal skin deformation and the ability to render of fast transient and wide frequency bandwidth tactile cues.

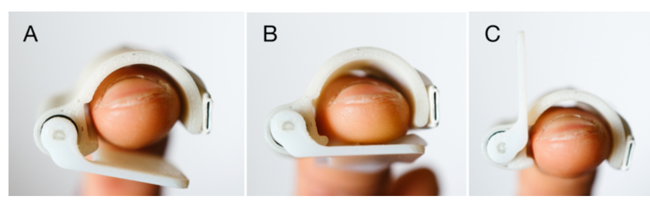

Figure 2. The device tactor in three different positions: (A) no contact, (B) contact, (C) full exposure of finger pad.

We performed a user study to explore the benefits of using our device to improve typing in VR. Typing is a particularly difficult task to render in virtual environments because traditional keyboards provide a rich array of tactile and kinesthetic cues such as keycap edges and key click force curves. To examine which forms of haptic feedback improved task performance the most, we tested users with four different haptic conditions (vibrotactile only; normal force only; combined; and no haptic feedback). The results show that the addition of any of the tested forms of haptic feedback improves typing performance, with the largest improvement coming from the conditions with normal force feedback.

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Table 1. A comparison of existing fingertip haptic devices. The device described in this paper is an order of magnitude lighter than existing devices, and its low profile maintains compatibility with Leap Motion hand sensors with no modification. Device specifications from [7].

Device	End-effector	Actuation technology	Type of provided stimuli	Weight at the fingertip (g)	Dimensions at the fingertip (mm)
Cheung	rigid tactor	1 DC motor + 1 piezoelectric actuator	contact, pressure, vibration	5	31 x 25 x 18
Solazzi et al.	rigid circular platform	4 DC motors	contact, pressure, curvature	56	55 x 45 x 35
Scheggi et al.	rigid circular platform	1 servo motor	contact, pressure	20	30 x 26 x 35
Schorr and Okamura	rigid tactor	3 DC motors	contact, pressure, friction	32	21.5 x 48.8 x 40.2
Prattichizzo et al.	rigid triangular platform	3 DC motors	pressure, curvature	30	45 x 24 x 31
Gabardi et al.	rigid circular platform	2 servo motors + 1 voice coil	contact, pressure, curvature, vibration	30	66 x 35 x 38
Sanfilippo et al.	1 motor	eccentric rotating mass (ERM) motor	vibration	~20	glove form factor

II. Related Work

Towards a solution to the lack of tactile feedback in VR, haptics through kinesthetic devices has been extensively explored [2][7]. Examples of these grounded devices include the Omega and the Phantom. While these devices can produce compelling sensations and large feedback forces, most kinesthetic devices are world grounded, and therefore have a limited range of motion. This represents a significant drawback, because VR experiences have increasingly been moving to room-scale and larger interactions with the innovations of inside-out tracking and full-room trackers. Grounded kinesthetic device generally cannot provide the large workspace needed for these types of interactions.

More recently there has been a growing field of research exploring wearable haptic interfaces that display various degrees of tactile and force feedback [7]. Such devices typically provide multiple degrees of normal or shear skin deformation [2], [3], [4], [5], sometimes coupled with relatively crude vibrational actuators like eccentric rotating mass (ERM) motors [9] or linear resonant actuators (LRAs) [3]. However, even in this new class of wearable haptic interfaces, devices remain relatively bulky and heavy (Table 1). Aside from user comfort drawbacks, the large size of current wearable haptic devices occludes too much of the finger to use commercial hand tracking systems like Leap Motion. This often necessitates the need for external motion capture systems like OptiTrack [3], which can be prohibitively expensive and are not easily scalable to larger interactions, or IMU-based tracking solutions, which pose challenges for noise and scaling to multiple fingers.

III. Device Design

A. Mechanical Design

Each fingertip tactile device has three mechanical components (Fig. 1). The first is a semi-rigid finger grounding interface that slip fits onto the distal phalanx. Grounding to the distal phalanx helps distribute the force from the skin deformation tactor, and the semi-rigid structure distributes the vibration from the piezoelectric actuator to create a stimulus that is perceived as originating from an external source. Each fingertip device has a total mass of 5 g, which is an order of magnitude lighter than existing devices (Table 1).

The second component of the devices is a flat tactor (330 mm^2) that is directly coupled to the output shaft of an internally geared micro DC motor. This tactor moves in 1 DoF and can achieve 270° of rotation, giving it the ability to make and break contact with the fingerpad. This range of motion also allows this device the unique capability of leaving the fingerpad completely unobstructed (Fig. 2), which may be desired for augmented reality applications such as augmenting real surfaces with virtual textures. The DC motor used has an internal 136:1 planetary gearbox, with an overall mass of 1.25 g and a stall torque of 550 g-cm at 6 V. The device is capable of up to 7.3 N of normal skin deformation.

The third component of the device is a piezoelectric bending actuator, which is capable of providing high fidelity vibrotactile feedback across a wide range of frequencies and amplitudes. The piezoelectric actuator chosen has a lead zirconate titanate (PZT) composition, with a mass of 1.4 grams, a resonant frequency of 275 Hz, a free deflection of 315 um, and a blocking force of 0.12 N.

B. Electronics Design

An Arduino Uno microcontroller was used to control the piezoelectric actuators and DC motors and to communicate with the rendered virtual environment.

An Adafruit motor shield (v2.3) was used to drive the DC motors. Each piezoelectric actuator was driven with a Texas Instruments DRV2667 voltage amplifier. The internal waveform synthesizer feature of the DRV2667 was used, allowing on-the-fly construction of complex haptic waveforms with designated amplitude, waveform, envelope, and duration, with minimal memory usage of the microcontroller. In order to drive multiple DRV2667 chips with a single microcontroller, an Adafruit TCA9548A 1-to-8 I2C multiplexer was used.

C. Virtual Environment and Tracking

Virtual environments were created using Unity 2017.3, in combination with the Leap Motion Core Assets 4.3.4 (which provides hand tracking and rendering) and the Windows Mixed Reality Toolkit (which provides inside-out tracking of the VR headset). A Samsung HMD Odyssey was used to display the virtual environment to users.

A Leap Motion sensor was mounted on the front of the headset to provide egocentric real time hand tracking. The Leap Motion uses three IR emitters and two IR cameras to sense the position of hands. The Leap Motion Core Assets processes the raw data from the sensor and provides a skeletonized hand model with positions, vector normals, and directions.

Within Unity, haptic interaction points (HIP) were placed on the virtual distal phalanxes of the thumb, index, and middle fingers. When a collision was detected between the HIP and an external object, a serial message would be sent from Unity to the microcontroller, triggering the appropriate DC motor rotation or piezoelectric waveform (depending on the chosen haptic condition). For the purposes of the typing user study (described in Part III), a simple contact/no contact model was used to trigger haptic feedback. However, the device is capable of modulating the amount of force feedback being provided, and this capability could be explored in the future for applications like stiffness rendering and grasping.

The neutral position of each device tactor was set for each participant roughly 3mm offset from the surface of the finger tip. This allowed full make-break contact capabilities while minimizing the time it took for the tactor to come in contact with the finger pad.

IV. Typing Performance User Study

To determine which haptic conditions were most helpful for improving typing performance, we performed a human-subject study under four different haptic conditions: no haptics, vibrotactile only, normal force only, and vibrotactile + normal force.

Ten participants (10 right-handed; ages 22-28; 4 male, 6 female) participated in the study. Two of the participants had prior experience with virtual reality devices and eight did not. The protocol was approved by the Stanford University Institutional Review Board, and all subjects gave informed consent.

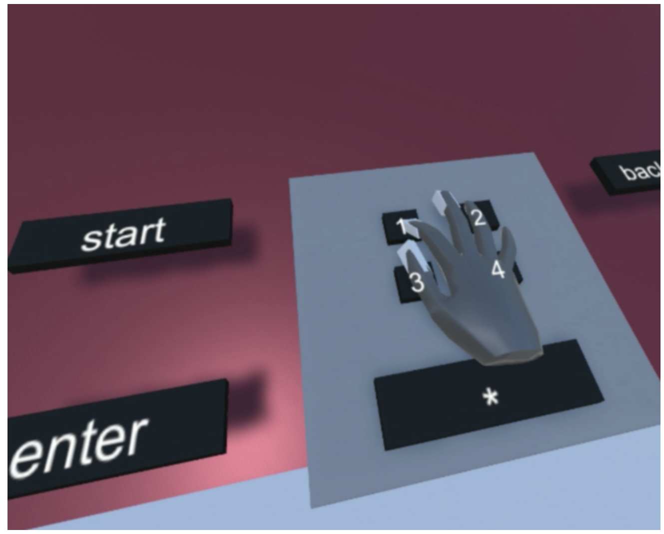

Figure 3. The virtual environment created for the VR typing user study. Users were presented with a five button keypad, as well as “Start”, “Enter”, and “backspace” keys.

Figure 4. A subject performing the user study while wearing the Samsung HMD Odyssey VR headset with a Leap Motion hand tracker mounted on the front of the headset. Users wore the haptic devices on the thumb, index, and middle fingers of their dominant hand.

A. Methods

In this experiment, participants were presented with a virtual environment consisting of a graphical five-button keypad, a simplified representation of their hand, and a display showing sequences of characters to copy (Fig. 3). During the task, the user would press the “Start” key to receive a sequence of 6 characters to copy, type the sequence using the keypad, and press “Enter” when done. Users were provided with “Backspace” to delete the previous entry and were instructed to find a balance between speed and accuracy that felt natural for them.

Participants began with a 4-minute familiarization phase, during which they experienced each of the four different haptic conditions and practiced typing and entering sequences. After the familiarization period, participants began a total of 35 to 45 trials. Each participant explored all 4 haptic conditions in a Balanced Latin Squares order. Each haptic condition was presented 5 trials at a time.

Table 2. Mean and standard error of typing speed of all subjects for each test condition with listed percent improvement relative to the no haptic condition.

Test Condition	Characters Per Minute		Relative Improvement
	Mean	Standard Error	
No Haptic	26.9	1.21	-
Vibrotactile	31.8	1.18	18.2%
Normal Force	33.0	1.1	22.5%
Vibrotactile + Normal Force	32.7	1.19	21.4%

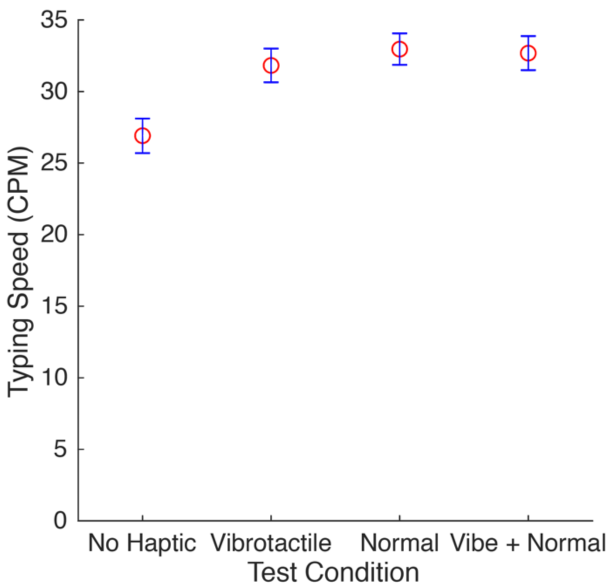

Figure 5. Mean and standard error of typing speed of all subjects for each test condition. (n = [100, 100, 110, 100])

After each haptic condition, participants were asked to quantify its helpfulness for typing, comfort, and realism. They verbally rated each factor on a 6-point Likert scale where 1 was the least helpful/comfortable/realistic and 6 was the most. To minimize the effects of fatigue, participants were instructed to rest as needed after each five trials.

B. Results

All forms of provided haptic feedback resulted in typing improvements relative to the no haptic control condition (One-way ANOVA, p = [0.015, 0.010, 0.015] for [Vibrotactile, Normal, Vibe+Norm]). Of the haptic conditions, the normal force condition yielded the largest relative improvement (22.5%), followed by the Vibrotactile + Normal force condition (21.4%) and the Vibrotactile condition (18.2%).

Table 2. reports typing speed mean and standard error for each condition and lists speed improvement relative to the no haptic condition. The assumption of normality for the trials was validated with a Lilliefors test. The error rate across all trials was too low to provide any significant comparative metrics between trials or conditions, likely because most users stopped to correct mistakes. However, the penalty of making and correcting mistakes is reflected in the typing speed. We also found no significant variations in task performance attributable to sex, haptics experience, VR experience, or QWERTY keyboard typing speed.

Verbal 6 point Likert responses between haptic conditions (n > 20) were analyzed using one-way ANOVA at a 5% significance level. Fig. 7 depicts the mean and standard error of these responses. Mean comfort variance was found to be significant between the vibrotactile and vibrotactile+normal conditions only. All three stimuli were significantly rated as more helpful than the no haptic condition, but no stimulus condition was determined to be significantly different than another. The vibrotactile condition was significantly rated as more real than all other presented test conditions, and the normal force condition was significantly rated to be more real than the no haptic condition.

The results of the post survey (Table 3) provided feedback (n = 10) on subjects' overall experience with the device on a 5 point Likert scale. These results indicate relatively neutral reactions to device use and comfort. All users agreed to some degree that they could understand the feedback provided by the device.

C. Discussion

The results of this study indicated that the addition of haptic feedback improved typing speed in a virtual environment. The lack of significant differences in task completion time between stimuli conditions suggests that the presence of any haptic feedback is sufficient to improve typing task speed. Verbal and written participant feedback suggested the possibility that normal force cues were too intense and could be overstimulating or incongruent with the sensation of pressing a button. Such over-stimuli could have been the cause of lower comfort and realism ratings for stimulus conditions which gave normal force feedback.

It is also important to note that while the experimental setup allowed subjects to use any of the three device-wearing fingers to press keys, not all subjects utilized all fingers. Future work could track the effects of haptics on finger usage. We note that the majority of subjects reported the most comfort and ease with the index finger, followed by the thumb and middle finger. The distribution of finger utility was primarily attributed to issues with tracking the fingers when the hand was rotated in an orientation that occluded fingers from view of the tracking device. It was observed that subjects tended to spread their fingers in order to resolve issues with tracking. It is possible that lower absolute ratings for Likert responses may have been the result of issues with tracking.

D. Comparison to Related Work

Because haptic sensations and specific user tasks vary widely, it is difficult to directly compare the results of our user study with results from other haptic device papers. However, some of our higher level findings do match what previous researchers have found.

For example, we found that all of our haptic conditions resulted in a significant improvement to typing speed (Fig. 5), and that adding more detailed feedback did not necessarily

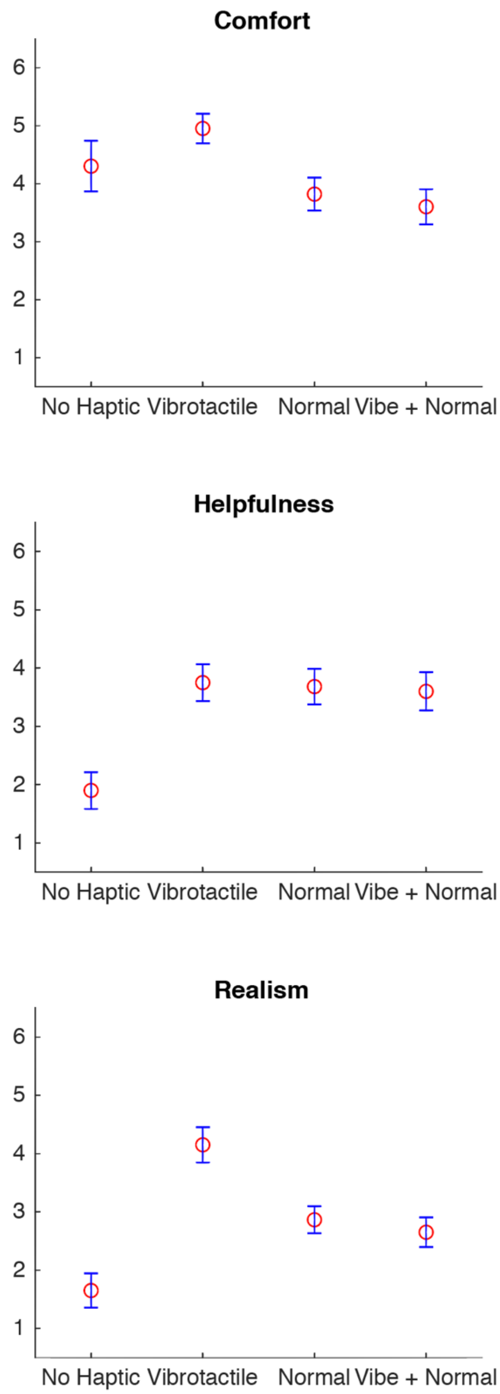

Figure 6. Mean and standard error of verbally reported Likert ratings following each trial where 1 = the least comfortable/helpful/realistic and 6 = the most. (n = [20, 20, 22, 20])

improve performance further. This finding is in line with work done by Microsoft Research comparing the effects of different forms of haptic feedback on a targeting task [1], where all forms of haptic feedback significantly improved task performance compared to the baseline no-haptic case. Interestingly, the vibrotactile case also showed no speed-accuracy tradeoff, whereas more detailed haptic feedback (like normal force and pin-arrays) reduced targeting error but also resulted in slowdowns in completion time. More research is necessary to determine how much haptic feedback is necessary for a convincing VR experience, and what degree of haptic realism is necessary to improve user performance on specific tasks. It may be the case that the balance between haptic realism and task improvement will be different depending on the specific user task.

V. Limitations and Future Work

While the results of our experiment confirm that there are clear benefits to adding haptics to complex multi-finger tasks like typing, much work remains to be done. A clear next step would be to conduct a study involving more fingers and a full QWERTY-style keyboard, and examining whether the benefits of adding haptics hold (or increase).

Further work could also analyze the effects of haptics on relative usage rates of multiple fingers in virtual reality typing tasks. The Leap Motion Sensor used for tracking in this experiment became a bottleneck at times when the device was unable to distinguish between fingers that are partially occluded or close together. A better tracking system might make users more likely to utilize more fingers.

The characteristics of the provided haptic feedback could also be improved. Users reported that the normal force provided by the device is quite prominent compared to the vibrotactile feedback, masking much of the sensation from the vibrations. Modulating the normal force applied to the fingers would both increase the comfort level of the device, and also give the ability to render things like stiffnesses and grasping. Improving the device's ability to fit different sized fingers would also improve user comfort levels. The DC motor used to actuate the tactor currently emits audible noise during operation. Finding a way to mask or reduce the noise could improve the user experience.

VI. Conclusions

We developed a novel ungrounded multi-fingertip tactile device capable of 1 DoF skin deformation with high fidelity vibrotactile cues in a form factor significantly smaller and lighter than existing devices. The small form factor is made possible by the implementation of a small gear motor actuating a single degree of freedom via a flat tactor and a thin piezoelectric actuator. The low profile design allowed for multi-finger tracking using a Leap Motion sensor. The device was tested by subjects performing a typing task in virtual reality and demonstrated that the device's provided haptic feedback improved VR typing speed by up to 22%. This study demonstrates that fingertip skin deformation combined with high fidelity vibrotactile cues can provide a compelling haptic experience appropriate for virtual reality tasks involving fine motor movement of multiple fingers.

VII. Acknowledgments

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