HapThimble: A Wearable Haptic Device towards Usable Virtual Touch Screen

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ABSTRACT

A virtual touch screen concept using an optical see-through head-mounted display has been suggested. With a virtual touch screen, the user's direct-touch interactions are allowed in much the same way as a conventional touch screen, but the absence of haptic feedback and physical constraint leads to poor user performance. To overcome this issue, we developed a wearable haptic device, called HapThimble. It provides various types of haptic feedback (tactile, pseudo-force, and vibrotactile) to the user's fingertip and mimics physical buttons based on force–penetration depth curves. We conducted three experiments with HapThimble. The first experiment confirmed that HapThimble could increase a users' performance when conducting clicking and dragging tasks. The second experiment revealed that users could differentiate between six types of haptic feedback, rendered based on different force–penetration depth curves obtained using HapThimble. Last, we conducted a test to investigate the similarity between the physical buttons and the mimicked haptic buttons and obtained a 90.3% success rate.

Author Keywords

Virtual touch screen; direct-touch interaction; wearable haptic device; haptic feedback without haptic constraint.

INTRODUCTION

The gradual maturing of the technology and industry related to optical see-through head-mounted displays (HMDs) has led to the advent of a future that allows everyday interactions within virtual environments. To maximize computing mobility using optical see-through HMDs, a vision-based virtual touch screen concept [20, 36] that allows users to directly manipulate a graphical user interface (GUI) on a virtual touch screen, using their hands, has been proposed.

Virtual touch screens are operated by direct-touch interaction using the users' hands alone, much like conventional physical touch screen devices.

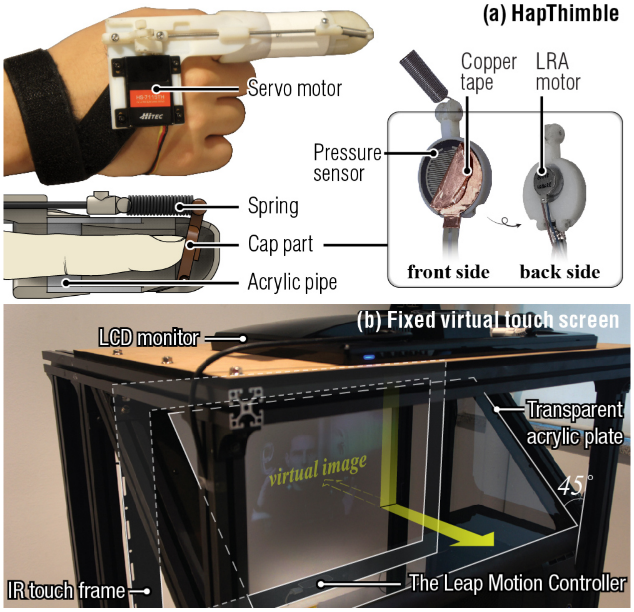

Figure 1. HapThimble system. Structures of (a) HapThimble and (b) fixed virtual touch screen.

Direct-touch interaction is intuitive, already implemented in many touch screen devices, and therefore, familiar to users. However, contrary to initial expectations, it is difficult to operate virtual touch screens with direct-touch interaction because of their intangibility.

The virtual surface of a virtual touch screen cannot realize a physical surface's two functions: providing haptic information, and physical constraint. Upon contact with a physical touch screens, users immediately receive a haptic sensation from the surface that indicates a transition from the idle state to the touched state. In contrast, in the case of a virtual screen, the user must rely solely on visual perception for an indication of the state transition when performing a clicking task, thus requiring greater attention from the user. Physical constraint, which is the second role of a physical surface, refers to the prevention of the penetration of the user's fingertip into the surface such that the intended touch state is easily and accurately attained. Due to this constraint, users have hardly any difficulty when dragging on a physical touch screen; whereas, the dragging task on a virtual touch screen is more demanding because it requires users to keep their fingers on an intangible virtual surface, in mid-air. Because of the absence of both functions, the performance of direct-touch

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interactions on a virtual touch screen is poor even for simple clicking and dragging tasks [8, 10, 24], so that users fail to accurately position their fingertips on the virtual surface, and often penetrate the surface [8].

Numerous studies have attempted to resolve this absence of haptic information and physical constraint. Especially in the fields of teleoperation and human–computer interaction, it is noticeable that the impetus is based on rendering realistic haptic feedback for virtual object manipulation using fixed-type haptic devices (e.g., PHANTOM, and the Haptic Station system) [1, 21, 27, 30, 39]. When a user presses on a virtual object, these devices provide haptic feedback by applying a force to the user's hand. This force stimulates the user's haptic sense, and physically restricts his or her hand movement relative to the virtual object. The restriction imposed by the exerted force serves as a physical constraint, and it makes user's hand manipulations rich and realistic.

Some studies have explored and conceptualized the roles of this restriction. Abbott et al. proposed a method that actively utilizes the restriction to support precise and reliable manipulation in teleoperation, which they named a "haptic virtual fixture" [1]. Wang & MacKenzie used the term "contextual haptic constraints" to explain the general role of the restrictions acting as physical constraints in a virtual object manipulation situation [38]. In this paper, we use the term "haptic constraint" to emphasize the fact that the restrictions correspond to a physical constraint. That is, a haptic constraint is a concept corresponding to a physical constraint. Due to the provision of this haptic constraint, these devices can support stable 2D handwriting in mid-air [39] and careful manipulation in robotic surgery [1].

Providing *haptic feedback with haptic constraint* is a good solution for an application such as robotic surgery. It would not, however, be an appropriate solution to everyday interactions with virtual touch screens. To exert a force, haptic devices generally have to be connected to the ground; therefore, they are not suitable for mobile use. In addition, the constraint could obstruct the users' hand movements when switching between real and virtual interaction objects. Therefore, when a user extends his or her hand toward a cup placed behind a virtual touch screen to take a sip of coffee, his or her hand movements should not be obstructed by either the virtual screen or haptic constraint. Moreover, as Lee et al. showed [23], novel spatial interaction using hand penetration can be realized when leaving user's hands free. To merge everyday interactions with virtual touch screens and make them usable, it would be necessary to provide not the restrictions, but rich haptic information. Namely, it is necessary to explore how to render appropriate *haptic feedback without any haptic constraint* and its roles.

Wearable haptic devices normally provide *haptic feedback without haptic constraint*. Because these wearable haptic devices are fixed to a part of the user's body (generally the hands or fingers), they cannot exert a net force capable of effectively restricting hand movements. However, their feedback qualities are relatively poor and monotonous. Some devices provide merely vibration to notify the user of their touching the surface upon making contact with a virtual target [10, 13, 40]. Some others provide pseudo-force feedback [3, 15, 26, 28, 33], but the feedback is very uniform.

In this research, in order to explore the roles of *haptic feedback without haptic constraint*, we developed a wearable haptic device, called HapThimble, and conducted three experiments. HapThimble provides several types of haptic feedback (tactile, pseudo-force, and vibrotactile feedback) to the user's fingertip, and renders different virtual button feedbacks based on force–penetration depth curves. It does not restrict the user's hand movements, thus allows the user's fingertip to penetrate the virtual surface. In the experiments, we investigated two aspects: how *haptic feedback without haptic constraint* performs roles other than physical constraint (experiment 1), whether the HapThimble can render different types of haptic feedback, and whether users can differentiate between those types of feedback (experiment 2 and 3). We found that *haptic feedback without haptic constraint* generally led to enhanced task performance in clicking and dragging tasks, while most users were able to distinguish between different types of virtual button feedback when using HapThimble.

RELATED WORK

Direct-touch Interaction with Virtual Touch Screen

A vision-based virtual touch screen concept was previously proposed [20, 36]. In these studies, it was assumed that a user would interact with a virtual touch screen similar to a physical touch screen device, but that slightly different techniques would need to be used because of technical limitations. Touch interactions with a physical touch screen generally conform to a two-state model [6], with transactions (e.g., click and drag) being determined based on the model and the absolute distance between the fingertip and the surface. However, Koh et al. used a time threshold to differentiate between a select operation and a drag-and-drop operation [20]. Tosas et al. used index finger nodding movements to achieve the click action [36]. In this study, to make touch interactions with a virtual touch screen as close as possible to a physical touch screen, we used the distance between the fingertip and the surface as the only feature to determine the state transition and transactions.

Haptic Feedback and Haptic Constraint

The reason for implementing haptic feedback is to support a user's manipulation of a virtual object. It supplements the user's lack of haptic sensation (haptic information) and also restricts the user's hand relative to a virtual object (role of haptic constraint). The haptic constraint has been treated as one important factor constituting haptic feedback. This not only restores the laws of physics between the user's hands and a virtual object by restricting the hands [12, 24, 38], but also actively guides and supports hand movements to enable stable and careful manipulation [1, 21, 30, 39]. Due to its importance and functionality, *haptic feedback with haptic constraint* has been studied by many researchers. However, to the best of our knowledge, there has been little research into *haptic feedback without haptic constraint*.

Wearable Haptic Devices

Generally, wearable haptic devices have been designed to satisfy too stringent requirements (e.g. small size, and wearable form factor), such that they cannot render rich haptic feedback. Some ring and thimble type wearable devices render constant and monotonous vibrotactile feedback with vibration motors while the user's fingertip is in the interaction space [10, 13, 40]. Some others provide pseudo-force feedback by tightening the user's fingertips with strings or straps to simulate the reaction forces corresponding to the pushing of virtual objects [3, 15, 28, 33] or the weights of virtual objects [26]. Glove-type wearable devices can provide reasonable force feedback because of their exoskeletal structure [5, 16], however, they are still heavy and bulky for everyday interactions. In addition, this type of device restricts finger movements, such that it cannot provide *haptic feedback without haptic constraint*.

Other Types of Haptic Device

Haptic devices using novel techniques (e.g., ultrasonic force fields, air vortices, and electrical muscle stimulation) have been proposed. An ultrasonic transducer array can create a force field in mid-air, so as to provide force feedback to the user [7, 14, 17, 31]. Although it offers the advantage of users being able to sense force feedback with their bare hands, it requires a large device. Recently, one research effort has proposed the use of a transducer array attached to a head-mounted display [31]. However, it is not applicable to optical see-through HMDs. Haptic devices using air vortices are another kind of tactile display [11, 34], but these also require large devices. Recently, there has been notable progress in the area of haptic feedback using electrical muscle stimulation (EMS). EMS haptic devices often take the form of wrist bands, making them suitable for mobile use. With EMS, a human's muscles can be controlled by electrical signals, such that the user's hand movements can be restricted [25, 37]. Thus, rather than a cutaneous sensation, it can simulate a kinesthetic sensation.

HAPTHIMBLE SYSTEM

The HapThimble system consists of two parts: the HapThimble device itself (Figure 1a) and a fixed virtual touch screen (fixed VTS; Figure 1b). The fixed VTS tracks the user's fingertip positions in real-time while presenting a virtual image. HapThimble provides *haptic feedback without haptic constraint* to the fingertip. This section provides a detailed explanation of the structure of both parts, the haptic feedback design and delay compensation process.

HapThimble

HapThimble is a wearable haptic device capable of providing tactile, pseudo-force, and vibrotactile feedback to a user's fingertip. It is designed to fit onto the user's index finger and the length of the device can be tailored to fit the user by changing the mid-section acrylic pipe. The outside diameter of the cylinder body is 25 mm, and its total length is 150 mm, width 60 mm, and weight 100 g.

The cap is in contact with the fingertip and provides the haptic feedback. It consists of a touch sensor (copper tape and the Arduino capacitive-sensing library), a pressure sensor (Interlink Electronics, FSR 402), and a linear resonant actuator (LRA motor) (Samsung Electro-Mechanics, Linear motor 0832; resonant frequency: 235 Hz; rated voltage: 1800 mV_{rms}; size: Φ8 × 3.2 mm). The touch sensor recognizes contact between the cap and the fingertip. The pressure sensor measures the pressure between the cap and the fingertip. The LRA motor provides vibrotactile feedback to the user. The cap and the servo motor (Hitec, HS-7115TH; operating speed: 0.12 s/60° at 6 V) is connected with a spring that moves back and forth to provide tactile, and pseudo-force feedback. A maximum force of 3.0 N can be provided by the servo motor. However, the net force cannot effectively restrict the user's hand movements. The servo motor and LRA motor impart kinesthetic and cutaneous cues, respectively, on the user's perception of compliance.

To independently control the servo motor and LRA motor, two Arduino boards (one UNO board and one MEGA 2560 board) were used. The UNO board was connected to the servo motor while the MEGA 2560 board was connected to the LRA motor, touch sensor, and pressure sensor.

Fixed Virtual Touch Screen

Fixed virtual touch screen was developed as an alternative type of virtual touch screen for experimental purposes which could be implemented comfortably in a laboratory environment. A 24" LCD monitor (ASUS VG248QE) and a transparent acrylic plate with a solar film (Plakos Co., SM50; visible light transmission: 51%; visible light reflectance: 21%) replaced the conventional optical see-through HMD, as shown in Figure 1b; this serves as the virtual display. The acrylic plate with solar film acts as a half-mirror that allows users to simultaneously view the displayed image and their hands in much the same way as with an optical see-through HMD (the high reflectivity of the half-mirror produces a bright display image while the user's hand is dark; the solar film helps to counteract this). The mirror image produced by this configuration assumes an exact position in 3D space and gives rise to an interposition failure problem [9], in much the same way as in stereoscopic optical see-through HMDs. Although not wearable like an HMD, it offers a good alternative for realizing a virtual display as a test apparatus, especially considering the lack of display and computing resources of commercial optical see-through HMD products.

To configure the virtual display into the fixed VTS, an Infra-Red (IR) touch frame (Nexio, NIB 320A) and The Leap Motion Controller were used. The IR touch frame tracks the 2D position of the fingertip on the virtual surface while The Leap Motion Controller tracks the 3D position of the fingertip. The fingertip position in the depth direction is an important variable to render haptic feedback.

Haptic Feedback Design

As shown in Figure 2, the HapThimble provides three different types of haptic feedback to the user's fingertips. The first type is provided when the fingertip comes in contact with the virtual touch screen, the second is given when the fingertip penetrates the virtual touch screen, and last type is given when the penetration depth of the fingertip exceeds a certain depth (D_{max}).

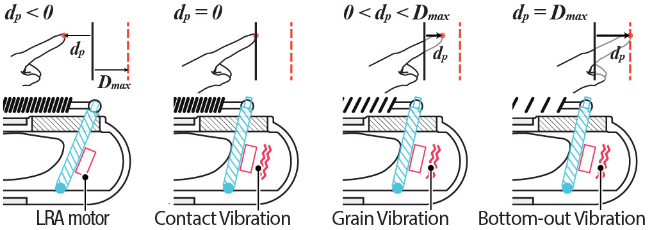

Figure 2. Three types of haptic feedback along the penetration depth of user's fingertip.

Contact haptic feedback

As the fingertip comes into contact with the virtual touch screen (at $d_p = 0$), the cap moves until it comes into contact with the user's fingertip. Previous research has confirmed the enhancement of the user's perception of a hard surface when a damped vibration is provided to coincide with the fingertip coming into contact with the virtual screen [22, 30]. The virtual surface of the virtual touch screen is thus sensed as being rigid when the touch sensor registers contact between the fingertip and the cap. This is achieved by the application of a single damped vibration (contact vibration) from the LRA motor. The signal used to generate the vibration is as shown in Figure 3. The signal duration is 30 ms and the amplitude correlates with the velocity of the fingertip in the depth direction at the contact position (V_d), ranging between 600 mV_{pp} and 1800 mV_{pp}.

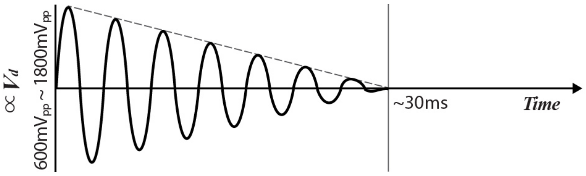

Figure 3. Signal to generate contact vibration.

Press/release haptic feedback

In the event of the fingertip penetrating ($d_p > 0$) the virtual touch screen, the servo motor moves the cap to provide pseudo-force feedback. To enable the HapThimble to render different pseudo-force feedback in response to different situations, the force exerted for the pseudo-force feedback is determined by the force–penetration depth curve (see the two examples shown in Figure 4). For example, when a flat-style GUI button is pressed, pseudo-force feedback having a linear correlation with the penetration depth is provided; similarly, when a GUI keyboard button is pressed, pseudo-force feedback can be provided in the tactile position such that the user senses a 'bump' from the keyboard. Prior to the fingertip reaching D_{max}, the force is determined by the press line (the red lines in Figure 4). Beyond D_{max}, however, the force is determined by the release line (green lines in Figure 4). The maximum force (F_{max}) generated by HapThimble is 3.0 N. D_{max} was determined to be 60 mm. As a result of a pretesting, the 95% upper bound of penetration depths was about 60 mm.

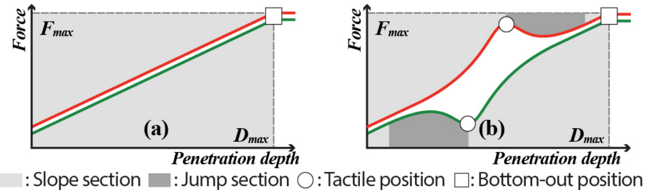

Figure 4. Two example force–penetration depth curves for (a) flat-style GUI buttons and (b) GUI keyboard buttons.

To enable the addition of a cutaneous cue to the pseudo-force feedback, vibrotactile feedback was provided based on the methods suggested by Kildal [18] and Kim and Lee [19]. The method of Kildal gave a short damping vibration (grain vibration) when the fingertip of a user pressing on a rigid surface passed through certain grain points. This method gave the user the sense that the rigid surface was compliant. Kim and Lee improved upon Kildal's method to mimic the rich haptic feedback of a physical button. To replicate the feedback from a physical button, they divided a force–displacement curve into slope and jump sections with reference to the tactile position. Grain vibration was provided in the slope section, and a jump vibration was given in the jump section to mimic the bump/collapse sensation immediately after the tactile position. In much the same way as in the work done by Kim and Lee, we also divided the curve into slope and jump sections and provided grain and jump vibration, respectively. However, we modify the method; instead of displacement, the penetration depth was referenced upon providing grain or jump vibrations.

The signal for the grain vibration is as shown in Figure 5. The signal duration is 18 ms with an amplitude that correlates with the pressure (P) detected by the pressure sensor, and is between 180 mV_{pp} and 900 mV_{pp}. The grain points were evenly distributed in the depth direction at 10 points/mm.

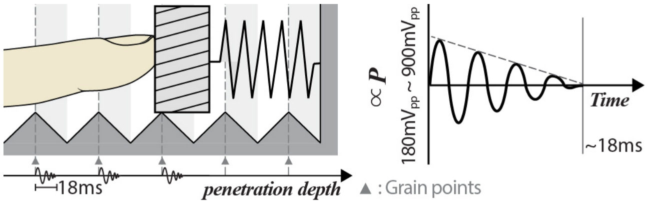

Figure 5. Signal to generate grain vibration.

The signals for the jump vibration is as shown in Figure 6. The signal is generated as the fingertip passes the tactile position, with the amplitude of the signal decreasing in proportion to the increase in the penetration depth, becoming 0 at the end of the jump section. The vibration continues while the fingertip is moving through the jump section ($|v_p| \geq 5\,mm/s$, where v_p is the velocity of the fingertip in the depth direction), such that if the motion of the fingertip stops, the vibration also stops ($|v_p| < 5\,mm/s$). The amplitude in the tactile position correlates with the area of the jump section (A) and is between 900 mV_{pp} and 1800 mV_{pp}.

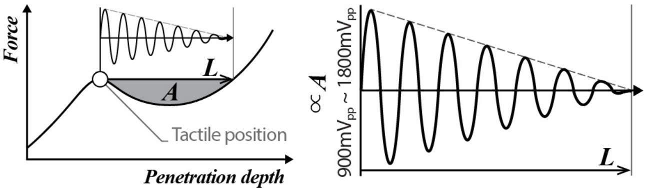

Figure 6. Signal to generate jump vibration.

Bottom-out haptic feedback

A short vibration (bottom-out vibration) is provided when the user's fingertip reaches the maximum depth ($d_p = D_{max}$). The bottom-out haptic feedback was designed based on the bottom-out feedback used in Kim and Lee's study [19]. The signal duration is 30 ms with an amplitude of 900 mV_{pp}. Unlike the contact and grain vibrations, the bottom-out vibration increases in amplitude over time (Figure 7).

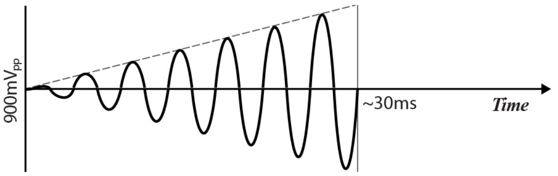

Figure 7. Signal to generate bottom-out vibration.

Vibrotactile feedback is ceased and a constant force feedback of F_{max} is provided when the fingertip passes the maximum depth ($d_p > D_{max}$). When the fingertip returns to within the maximum depth, haptic feedback is rendered based on the release line of the force–penetration depth curve.

Limitations of vibrotactile feedback design

According to Kildal [18] and Kim and Lee [19], the vibration frequency is an important factor in user's compliance perception. Especially, Kim and Lee designed grain, jump, and bottom-out vibration with different frequencies. However, we used the LRA motor to reduce the size of HapThimble, which limited the frequency of the vibrotactile feedback to 235Hz because of the mechanism of LRA motor.

Compensating for Servo Motor Delay

Between the user's fingertip coming into contact with the virtual touch screen and the cap coming into contact with the fingertip, the servo motor would incur a critical delay in excess of 60 ms. To reduce the delay caused by the servo motor, we attempted to proactively start the servo motor. First, the position data from the Leap Motion controller was smoothed using the weighted moving average. Second, with D_t as the servo motor delay, dead reckoning was used to predict the penetration depth after D_t, and the predicted depth (d_{pre}) was used to start the servo motor when $d_{pre}=0$. If the penetration depth is d_p, and the fingertip depth velocity and acceleration are v_p and a_p, the predicted depth (d_{pre}) as determined with the reckoning equation will be as follows:

$$d_{pre} = d_p + v_p \times D_t + (0.5 \times a_p \times {D_t}^2) \tag{1}$$

A short test was conducted to determine the value of D_t. Three test subjects were subjected to a series of click tasks using HapThimble. The time taken between the IR touch frame recognizing a touch and the touch sensor sensing a touch between the cap and the user's fingertip was measured. The delay time with a 95% confidence interval was found to be 84.4 ms to 112.1 ms. To compensate for the delay and prevent haptic feedback from occurring prior to contact, a delay time near the lower bound was selected. A fine-tuning process yielded a D_t value of 80 ms. The servo motor delay thus fell to an average of 20 ms after delay compensation.

EXPERIMENTS

Experiment 1

The roles of *haptic feedback without haptic constraint*, and physical constraint were compared through a within-subjects experiment. The experiment was conducted under four experimental conditions: ***Bare***, ***Tactile***, ***Force***, and ***Physical***. Under the ***Bare*** condition, the test subjects were given no haptic feedback. Under the ***Tactile*** condition, only contact haptic feedback was given to the test subjects through HapThimble. Under the ***Force*** condition, contact, press/release, and bottom-out haptic feedback were given to the test subjects through HapThimble. In this case, the press/release haptic feedback conforms to a linear force–penetration depth curve (Figure 4a). Last, under the ***Physical*** condition, an acrylic panel was attached immediately behind the virtual touch screen to mimic a physical touch screen. Haptic information and physical constraint were thus provided using this configuration. A transparent film (Plakos Co., Clear 2MIL) was attached to the acrylic panel to reduce the friction of the acrylic panel. The top of the film was treated with an anti-scratch coating. This coating is commonly used in protective films for smartphones, thus making the touch experience under the ***Physical*** condition very similar to that of a conventional touch screen device. Experiments were conducted with the previously described HapThimble system (HapThimble and fixed VTS). Test subjects wore HapThimble for the ***Tactile*** and ***Force*** conditions and used their bare hands under the ***Bare*** and ***Physical*** conditions.

Twelve right-handed test subjects without any vision impairment were recruited (seven males and five females; mean age of 25.5 years). The subjects were asked to conduct clicking tasks and dragging tasks accurately and quickly, under the four conditions. Prior to testing, each subject was given five minutes to practice and become accustomed to the conditions. To reduce residual errors, the test subjects performed the clicking task and dragging task under an order of conditions as determined by the Latin-square design. Each session consisted of 20 clicking task trials and 20 dragging task trials, with each subject completing five sessions in total. A total of 90 minutes were required for each test subject to complete the test, after which, an interview was conducted.

Procedure of clicking and dragging tasks

To ensure that the start point was always the same, the test subjects were required to position their fingertips to a point 10 cm from the virtual touch screen. During a three-second countdown, if the user successfully kept their fingertip 10 cm from the virtual screen, a square target was presented. For the clicking task, a single white target appeared while for the dragging task, two targets (one white, the other gray) appeared. All of the targets were identical in size with dimensions of 55 × 55 mm and their location was randomly decided. For the dragging task, however, the distance between the white and the gray targets was fixed to 20 cm. The target size was determined by several pilot tests. In the pilot tests, the bulkiness of the HapThimble led to high error rates. To eliminate the interference caused by the limitations of the test apparatus and to focus on a comparison of the haptic feedback conditions, we determined an optimum size. The clicking task involved touching and releasing the interior of this target. The dragging task involved touching the interior of the white target, maintaining contact, dragging the white target to the gray target, and then releasing it within the gray target. If the user failed at any point during the click or drag task, they were not required to start anew and could start from their current position.

Visual depth cues

The test subjects were provided with two visual depth cues. The first was a shadow image corresponding to their hand position. The second involved the center of the target gradually becoming darker as the penetration depth increased.

Results

With the repetition of the sessions, the test subjects exhibited an improvement in their performance as shown in Figure 8. A results analysis for this experiment used the results from the 5th session.

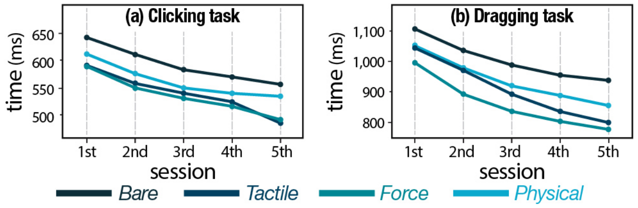

Figure 8. Mean task completion times over 5 sessions. (a) Clicking task, and (b) dragging task

Test results were divided according to three timings and then analyzed. These timings were the task completion time, the addressing time, and the positioning time. The task completion time is the time from the presentation of the target to the completion of one trial. The addressing time is the time that elapses between the presentation of the target and the subjects touching the virtual touch screen. The positioning time is the time that elapses between the subjects touching the target and they releasing it. Figure 9 shows each condition's mean task completion time, mean addressing time, and mean positioning time. The four conditions had a statistically significant effect on the three kinds of mean times for both the tasks (Repeated measures ANOVA; $p < 0.05$). Those pairs indicated by '*' in Figure 9 had significant differences (Bonferroni pairwise comparisons; $p < 0.0125$). The performance in the ***Bare*** condition was the worst among all the conditions. In the clicking task, the mean task completion times under the ***Tactile*** and ***Force*** conditions were about 11% less than that under the ***Bare*** condition. For the dragging task, the performance under the ***Tactile*** and ***Force*** conditions was about 14.6 and 17.1% better than that under the ***Bare*** condition, respectively. Overall, the performance under the ***Tactile*** and ***Force*** conditions was better than that under the ***Bare*** and ***Physical*** conditions.

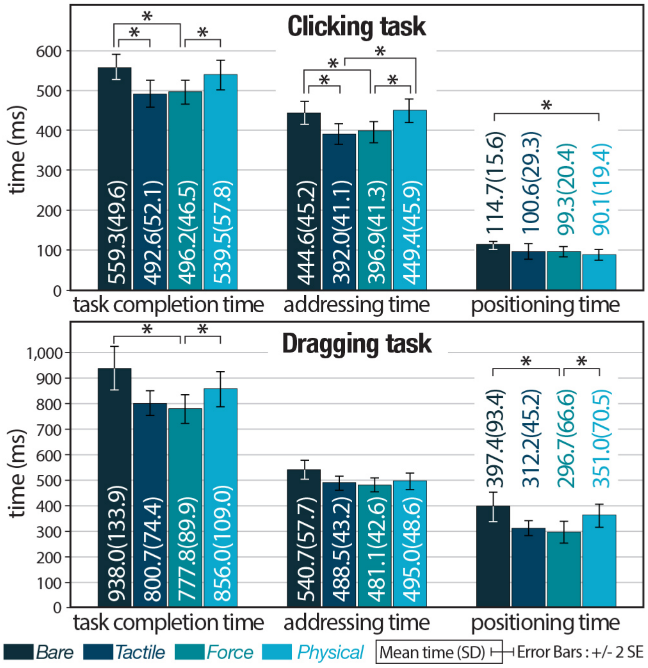

Figure 9. Mean task completion time, mean addressing time, and mean positioning time.

The error rate under each condition is given in Table 1. "Error in touch" refers to a subject's failure to accurately touch the interior of the target. "Error in release" refers to the subject's ability to touch the target accurately but inability to release his or her fingertip within the target. Regardless of the condition, the error rate was similar for the click task. For the dragging task, however, the ***Bare*** condition led to a significantly higher error rate than the other conditions.

Clicking task (error rate / number of errors)

	Error in touch	Error in release	Total error
Bare	1.67% / 4	0.83% / 2	2.5% / 6
Tactile	0.83% / 2	0.42% / 1	1.25% / 3
Force	0.42% / 1	0.42% / 1	0.83% / 2
Physical	1.25% / 3	0% / 0	1.25% / 3

Dragging task (error rate / number of errors)

	Error in touch	Error in release	Total error
Bare	3.33% / 8	8.75% / 21	12.08% / 29
Tactile	0.83% / 2	1.25% / 3	2.08% / 5
Force	0% / 0	1.25% / 3	1.25% / 3
Physical	2.08% / 5	0.83% / 2	2.92% / 7

Table 1. Error rates and numbers of errors.

The means of the maximum penetration depths determined under the three conditions, except for the ***Physical*** condition, are shown in Figure 10a. There were no significant differences in the maximum penetration depths for the two tasks performed under the three conditions (Repeated measures ANOVA; $p > 0.05$). Even a comparison of the trajectories of the fingertip movements in the dragging task revealed no notable differences (Figure 10b).

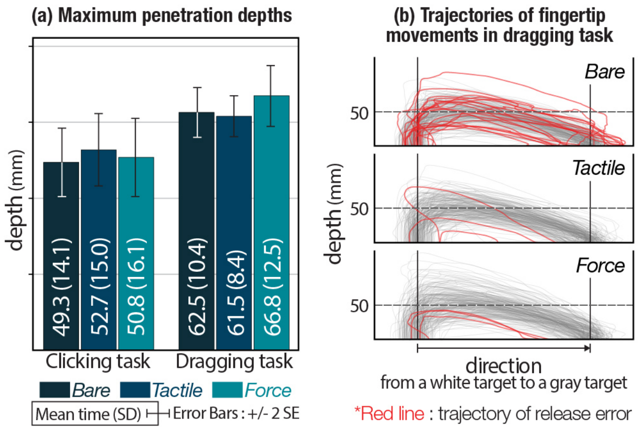

Figure 10. (a) Mean of maximum penetration depths, and (b) trajectories of fingertip movements in dragging task

Findings and interpretation

As was shown experimentally, the levels of performance that could be achieved in the clicking and dragging tasks were similar for the ***Tactile*** and ***Force*** conditions, and for the ***Bare*** and ***Physical*** conditions. It was also found that the ***Tactile*** and ***Force*** conditions led to better levels of performance than the ***Bare*** and ***Physical*** conditions.

The addressing times under the ***Tactile*** and ***Force*** conditions were shorter than that under the ***Physical*** condition. Under the ***Physical*** condition, the subjects became aware that hitting the acrylic panel at high speed would result in significant pain. The subjects, therefore, attempted to prevent this from occurring by moving relatively slowly. In contrast, under the ***Tactile*** and ***Force*** conditions, haptic feedback was provided but did not physically block the user's fingertips thereby allowing the subjects to quickly address their fingers. Similarly, in comparison with the ***Bare*** condition, which did not provide any constraint, the addressing time under the ***Tactile*** and ***Force*** conditions was the shortest. The reasoning for this was that the haptic feedback provides the user with notification of the instant at which the user's finger makes contact with the subject, thus enabling the subjects to predict the contact and move their fingertips quickly.

When performing dragging tasks, the ***Tactile*** and ***Force*** conditions led to a shorter positioning time than was possible under the ***Bare*** condition. Taking into account the high error rate under the ***Bare*** condition, the shorter positioning time should be related to the tactile and force feedback reducing the release error during positioning rather than the increase in the speed of the finger positioning. Under the ***Force*** condition, the intensity of the force feedback corresponding to the penetration depth seemed to support the subjects' perception of the position of their fingertip. On the other hand, the tactile feedback remains constant regardless of the penetration depth, such that the subject cannot perceive the depth of his or her fingertip in the same way they could under the ***Force*** condition. It is assumed that, when the HapThimble cap comes into contact with the fingertip to provide tactile feedback, the fingertip remembers that position as a result of proprioception and moves with respect to the position while performing the dragging task.

Surprisingly, the positioning time under the ***Physical*** condition was similar to that under the ***Bare*** condition. It was anticipated that the acrylic panel would act as a physical constraint therefore resulting in a difference in the positioning time. However, such a difference was observed only for the clicking task and even that was negligible (24.6 ms). For the dragging task, for which we anticipated a large difference, there was no notable difference (mean difference: 36.4 ms; Bonferroni pairwise comparisons, $p = 0.758$). Considering the large release error under the ***Bare*** condition, the lack of any notable difference implies that the speed of the user's fingertip movement on top of the acrylic panel was very slow. In the post-experiment interview, the subjects complained that the friction of the acrylic panel made it difficult to move, even though it was covered with the slippery transparent film, and thus prevented rapid movements. From these results, we were able to deduce that, although physical constraint encourages stable user interaction with the virtual touch screen, it does not guarantee better performance than *haptic feedback without haptic constraint* in simple tasks like clicking or dragging.

An examination of the maximum penetration depth and fingertip trajectories of conditions reveals that, with the exception of the ***Physical*** condition, *haptic feedback without haptic constraint* has little effect on a fingertip's penetration or the trajectory of the fingertip movement.

We were consequently able to investigate the effects of the *tactile and force feedback without any haptic constraint*, and the effects of physical constraint on the direct-touch interaction with the virtual touch screen. The experimentally found roles of the *tactile and force feedback without haptic constraint* and physical constraint are as follows:

- Tactile and force feedback provide instant notification of contact thereby allowing quicker addressing movements.
- Tactile and force feedback aid with the perception of the finger's depth position and allow the positioning movements to be performed in a more stable manner.
- Tactile and force feedback neither inhibits nor reduces the penetration and do not affect the user's hand movements.
- Physical constraint leads to slower addressing movement due to the user's fear of collision.
- Physical constraint enables stable positioning movement but does not always guarantee better performance.

Experiment 2

HapThimble provided the test subjects with six types of virtual button feedback mimicking six different physical buttons. An ABX test was conducted to determine if the subjects could differentiate between the types of virtual button feedback.

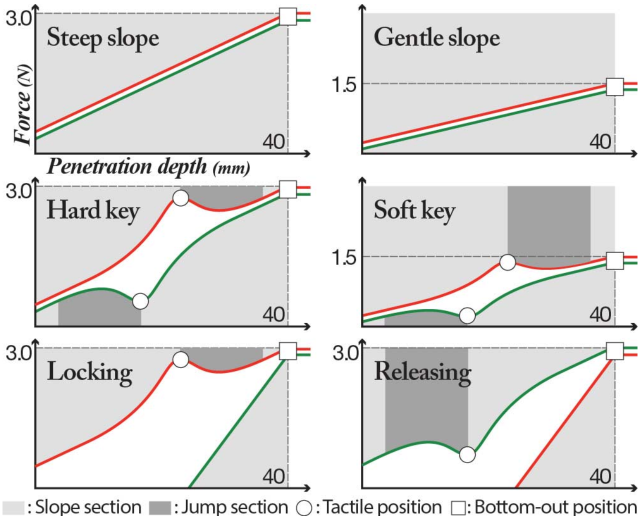

Figure 11. Force-penetration depth curves of six virtual buttons.

Based on a non-locking push-button switch, a rubber dome key switch, and a self-locking push-button switch, six types of virtual button feedback were designed: Steep slope, Gentle slope, Hard key, Soft key, Locking, and Releasing. We were unable to find the force–displacement curves for the three switches but it was possible to deduce these curves based on their internal structure and pressing sensation. The non-locking push-button switch exhibited a linear curve because of its spring component. The curves for the rubber dome key and self-locking push button were decided based on the structures of their respective tactile points. The Steep and Gentle slopes assume a linear curve at the penetration depth that is similar to that of the non-locking push-button switch. In other words, the force and amplitude of the vibration of the Steep slope is double those of the Gentle slope. Hard and Soft keys were designed based on the rubber dome key switch. The two curves were found to have similar shapes but the force and amplitude of the vibration for the Hard key at a given penetration depth are double those for a Soft key. Locking and Releasing are virtual button feedbacks corresponding to the turning on (Locking) and turning off (Releasing) of the self-locking push button. The release line for Locking and the press line for Releasing are identical. The press lines for Hard key and Locking are the same, as are the release lines for Hard key and Releasing. The travel length of the six virtual buttons were determined to be 40 mm. Their respective force–penetration depth curves are as shown in Figure 11.

This experiment was conducted under two conditions: the ***F+V condition*** and the ***F condition***. The ***F+V condition*** provided both pseudo-force and vibrotactile feedbacks. The ***F condition*** provided only pseudo-force feedback.

An ABX test was conducted for the following six pairs: 'Steep slope-Gentle slope,' 'Hard key-Soft key,' 'Locking-Releasing,' 'Steep slope-Hard key,' 'Hard key-Locking,' and 'Steep slope-Locking.' Ten right-handed test subjects without any vision impairment were recruited (five males and five females; mean age: 26.3). All of the pairs were tested ten times with each subject. Five out of the ten subjects progressed from the ABX test under the ***F+V condition*** to the ABX test under the ***F condition***. The remaining five progressed in reverse order.

The test subjects were given a short period of time to experience the six types of virtual button feedback prior to the ABX testing. The subjects were given sufficient time to experience and compare two types of virtual button feedback. Subsequently, each subject was given a blind stimulus, randomly selected from the two types of feedback, and was asked to identify the type of feedback that they had received. No time limitation was imposed on their decision and they were asked to choose carefully.

Apparatus and experimental setup

A stereoscopic 3D display was set up using active-shutter 3D glasses (NVidia 3D vision kit) and a 120-Hz LCD monitor (ASUS VG248QE) to enhance the user's depth perception. The 3D image obtained from the active-shutter 3D glasses was dim and could not be viewed under indoor lighting. Tests were conducted with the lights turned off to allow the subjects to identify the 3D image. Even though the lights were turned off, the subjects could still see their hands under the light of the LCD monitor. In addition, the subjects wore 3M earplugs to prevent them from distinguishing between the different types of virtual button feedbacks based on the sound emitted by HapThimble.

Visual depth cue

A stereoscopic 3D display was used to present a cubic red button attached to a wall to the test subjects. The button's motion ranged between 0 and 40 mm, corresponding to the fingertip penetration depth and thereby providing a sense of actually pressing the button. For motion of less than 40 mm, the button was red, but beyond 40 mm the button turned blue. Identical visual cues were provided for the six virtual buttons.

Results

	F+V condition	*F condition*
Steep slope-Gentle slope	100% (0)	100% (0)
Hard key-Soft key	99% (0)	100% (0)
Locking-Releasing	97% (0)	91% (3)
Steep slope-Hard key	96% (0)	94% (1)
Hard key-Locking	94% (1)	90% (2)
Steep slope-Locking	96% (1)	92% (2)
Total	97% (2)	94.5% (8)

Table 2. ABX test result.

Table 2 lists the results of the ABX tests. The percentages refer to the percentages of correct responses while the number in parentheses indicates the number of subjects who failed the ABX test (a subject had to attain nine correct responses to satisfy a 95% confidence level for each pair). The gray boxes indicate those pairs that did not satisfy the 95% success rate. These results indicate a higher success rate when both pseudo-force and vibrotactile feedbacks are provided rather than just pseudo-force feedback. Prior research has found that both kinesthetic and cutaneous cues are complementary factors for compliance perception [4, 22, 35], with the above results concurring with these findings.

In those cases where only the stiffness differs, such as between the Steep slope-Gentle slope pair and Hard key-Soft key pair, it was possible to distinguish between the different types of virtual button feedback regardless of the vibrotactile feedback. In addition, for the other four cases in which the shapes of the two force–penetration depth curves are not similar, it was difficult to distinguish between them based solely on pseudo-force feedback. Additionally, the provision of a cutaneous cue enhanced a subject's ability to distinguish between the types. However, the subjects were unable to attain a 95% success rate when attempting to distinguish between the Hard key-Locking pair, even with both pseudo-force and vibrotactile feedback. The subjects found the Hard key-Locking pair to be more difficult to distinguish between because their press curves were identical.

As a result of this experiment, we confirmed that HapThimble could provide a variety of distinguishable types of virtual button feedback. In addition, in those cases in which the pseudo-force feedback is insufficient to simulate subtly different force–penetration depth curves, the addition of vibrotactile feedback will act as a supplement.

Experiment 3

We investigated whether the subjects were able to associate a virtual button rendered by HapThimble with the corresponding physical button. A non-locking push-button switch ($\mathbf{A_p}$), self-locking push-button switch ($\mathbf{B_p}$), and rubber dome switch ($\mathbf{C_p}$) were replicated. For replicating, Steep slope, Hard key, Locking, and Releasing in experiment 2 were used. Steep slope ($\mathbf{A_v}$) for $\mathbf{A_p}$, and Hard key ($\mathbf{C_v}$) for $\mathbf{C_p}$ were mapped. The self-locking push-button switch was mapped with an alternating Locking and Releasing sequence ($\mathbf{B_v}$). The Releasing phase was given by taking the Locking phase from the contact position, through the bottom-out position, to full release. Similarly, the Locking phase was given by carrying through the Releasing phase.

The apparatus, experimental setup, and visual depth cue were identical to those used in the experiment 2. The same ten subjects as those who performed the previous test were used and each subject took about 5 minutes to complete the test. The test subjects first experienced the three physical buttons ($\mathbf{A_p}$, $\mathbf{B_p}$, and $\mathbf{C_p}$). Then, the subjects were presented with ten of each of the virtual buttons ($\mathbf{A_v}$, $\mathbf{B_v}$, and $\mathbf{C_v}$), in random order, totaling 30 buttons. The subjects were asked to match the presented virtual buttons with the physical buttons.

Results

Only one subject correctly matched all of the 30 virtual buttons to the corresponding physical buttons. None identified $\mathbf{C_v}$ as either $\mathbf{A_p}$ or $\mathbf{B_p}$ (100% success rate) but the remaining nine subjects confused $\mathbf{A_v}$ with $\mathbf{B_p}$, or $\mathbf{B_v}$ with $\mathbf{A_p}$. The subjects confused $\mathbf{A_v}$ with $\mathbf{B_p}$ a total of 12 times but correctly matched $\mathbf{A_v}$ with $\mathbf{A_p}$ 88 times (88% success rate). $\mathbf{B_v}$ was incorrectly identified as $\mathbf{A_p}$ a total of 17 times and $\mathbf{B_v}$ was successfully matched with $\mathbf{B_p}$ 83 times (83% success rate). Out of the 300 attempts, 271 correct identifications were made, corresponding to a success rate of 90.3%.

After completing the test, the subjects stated that the rubber dome key switch ($\mathbf{C_p}$ and $\mathbf{C_v}$) was easiest to identify, due to the two clear tactile positions along the press and the release lines. In addition, they noted that differentiating between a self-locking push-button switch and non-locking push-button switch was difficult. A few subjects said that it was difficult to distinguish between the Locking and the Releasing phases when trying to identify the self-locking push button and, in fact, they often failed to do so. In essence, the subjects confused the press/release line of Releasing/Locking with that of the non-locking push button.

When asked whether the virtual buttons successfully simulated the physical buttons, most subjects responded that they did not. The subjects experienced a bump/collapse sensation when their fingertips reach the tactile positions. They were able to recognize the characteristics of the physical button being mimicked, but stated that it was not the same as the sensation given by the actual physical button. They were unable to experience the sharp feedback given by the physical button. The displacement of the physical buttons was about 5 mm. However, the virtual button feedback had a large range (40 mm), which gave the user a soft, dull impression. HapThimble was able to create the bump/collapse sensation of the tactile position needed to distinguish between physical buttons but only abstract and smooth feedback was possible due to the difference in scale of the travel of the physical and virtual buttons.

DISCUSSION

Roles of Haptic Feedback without Haptic Constraint

Experiment 1 revealed the advantages of having no constraint on the user's hand movements when providing *haptic feedback without haptic constraint*. In the clicking and dragging tasks, the overall performance was found to be enhanced relative to there being no haptic feedback and physical constraint conditions. A user experiences no movement restrictions and is able to quickly perform tasks, which enhances the addressing movement with the provided haptic information, as well as the ability to stably perform tasks. *Haptic feedback without haptic constraint* notifies a user of the instant at which contact is made with the virtual touch screen, and enhances the users' awareness of the penetration depth of their fingertips. There is, however, a difference in that tactile feedback relies on proprioceptive sensation while force feedback uses kinesthetic sensation to aid in depth perception. Simply put, the former would require a larger cognitive load than the latter, but this issue requires further study.

Experiments 2 and 3 showed that both the pseudo-force and vibrotactile feedback contribute to the ability to distinguish between the different types of virtual button feedback. Pseudo-force and vibrotactile feedback provides kinesthetic and cutaneous cues, respectively. As revealed by previous research, both cues mutually function in compliance perception [4, 22, 35]. Force feedback is sufficient for recognizing the compliance of the virtual button, but vibrotactile feedback supplements the recognition in those cases in which the force curves are subtly different.

The results of experiment 1, which indicate that there is no change in the performance between the physical constraint and no haptic feedback is surprising and roughly contradicts the results of previous research [10, 24]. We required the subjects to position their fingertips 10 cm away from the virtual touch screen. This may not be a large distance but it is sufficient to prevent the subjects from tapping the virtual touch screen as a result of a simple wrist movement. Therefore, the subjects were not able to tap the surface but rather were asked to produce a motion closer to a stabbing motion. As a result, the physical constraint constituted an obstacle to the subjects. This difference in the tasks and the experimental setup may have produced the results that were at odds with those of previous research. Despite this, we were able to experimentally confirm that physical constraint enables stable positioning movement relative to no haptic feedback.

From the results of the three experiments, it is clear that mimicking reality with haptic constraints is not always the best solution to everyday interactions with virtual touch screens. Although a virtual touch screen is a counterpart to a physical touch screen, it does not always require haptic constraint. Even without the provision of haptic constraint, the support of direct-touch interaction with a virtual touch screen and the provision of a variety of quality haptic compliances to users can be possible with haptic information alone. The ability to determine the roles of each type of haptic feedback and selectively provide the correct feedback for optimum application to a virtual touch screen is important.

Design Guidelines of Wearable Haptic Device

The small size and wearable form factor of wearable haptic devices make the implementation of actuators that provide sufficient haptic feedback extremely difficult. Therefore, a wearable haptic device must be designed such that is selectively uses all of the necessary haptic feedback. Herein, we suggest tentative guidelines for selecting the necessary haptic feedback when designing a wearable haptic device.

- Haptic feedback is not required for applications that primarily rely on clicking tasks. The error rate remains constant with and without haptic feedback although task time falls by 10% with the haptic feedback.
- Haptic feedback for depth perception is necessary if the application primarily relies on dragging tasks.
- If virtual button feedback is not required, the provision of only tactile feedback can cover most operations.
- Providing virtual button feedback can be achieved using only pseudo-force feedback, which can provide a variety of types of feedback. Vibrotactile feedback can be used to supplement this.

Applications of HapThimble

HapThimble can render tactile positions in mid-air. If a click event occurs after passing the tactile position, as in the case of a typical mouse button, it is possible to make a virtual touch screen conform to the general three-state model [6]. Then, a user can move his or her finger along the surface with a touch sensation in State 1, while a slight movement of the finger into the surface changes the state from State 1 to State 2 with a bump/collapse feel. This makes the interaction space thicker; direct-touch interactions on a virtual touch screen would thus become more stable and comfortable.

In addition, due to HapThimble providing *haptic feedback without haptic constraint*, the penetration of a user's hand into a virtual interaction space can be actively utilized. This feedback can effectively support a hand penetrating a multi-layer virtual touch screen (akin to the scenario demonstrated by Lee et al. [23]) rather than a single-layer virtual touch screen. A user can easily reach a specific screen among these screens, and can directly manipulate the screen by using the feedback.

Miniaturization of HapThimble

The miniaturization of HapThimble is essential despite, as mentioned above, it being very difficult to reduce the size while preserving the feedback quality. Fortunately, a novel technique for providing pseudo-force with human haptic illusion and asymmetric vibration has been proposed [2, 29]. This technique needs only a vibration motor, thus can be utilized for the miniaturization and integrated with the vibrotactile feedback of HapThimble. It would appear to be worthwhile to attempt to apply this technique to miniaturization research.

CONCLUSION

The advantages of the *haptic feedback without haptic constraint* for the direct-touch interaction with a virtual touch screen were investigated, and a wearable haptic device which simulates various physical buttons was proposed. Based on the results of this work, we hope that a compact wearable haptic device can be developed, which would enable easy interaction with a virtual touch screen. In addition, there is room for investigation on haptic feedback for novel spatial interactions with a virtual touch screen.

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