

Haptic Feedback Design for a Virtual Button Along Force-Displacement Curves

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ABSTRACT

In this paper, we present a haptic feedback method for a virtual button based on the force-displacement curves of a physical button. The original feature of the proposed method is that it provides haptic feedback, not only for the “click” sensation but also for the moving sensation before and after transition points in a force-displacement curve. The haptic feedback is by vibrotactile stimulations only and does not require a force feedback mechanism. We conducted user experiments to show that the resultant haptic feedback is realistic and distinctive. Participants were able to distinguish among six different virtual buttons, with 94.1% accuracy even in a noisy environment. In addition, participants were able to associate four virtual buttons with their physical counterparts, with a correct answer rate of 79.2%.

Author Keywords

Haptic; tactile feedback; virtual button; force-displacement curve; rigid surface

ACM Classification Keyword

H.5.2. Information interfaces and presentation (e.g., HCI):
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INTRODUCTION

A virtual button on a touchscreen lacks haptic feedback when compared with a physical button. A physical button provides both force and tactile feedback, which stimulate kinesthetic and cutaneous senses, respectively. Nevertheless, technology for the provision of force feedback on a touchscreen, has not yet matured, and this is especially so for mobile devices [8]. Studies on haptic feedback for a touchscreen have so far focused mainly on tactile feedback through tactile actuators [4, 8, 10, 13, 14]. Therefore, most haptic feedback designs for a virtual button ignore kinesthetic feedback and focus on modeling “click” vibrations that occur at the state-transition moments of a button [1, 4, 8, 10, 11, 12, 13].

A physical button provides haptic feedback throughout its full travel range – from the moment of touch, through the point of collapse, to the bottom of the button travel. On the other hand, most current haptic feedback designs for a virtual button provide haptic feedback only for the point of collapse, for the reason that we mentioned above. This is clearly an oversimplification of the haptic feedback of a real button, and we speculated that haptic feedback for a virtual button would be more realistic and distinctive if kinesthetic feedback before and after the point of collapse is also considered in a haptic-feedback design.

A physical button has its own force-feedback characteristics. These characteristics are represented by force-displacement curves that describe in a quantitative manner the kinetic characteristics. For this reason, most button manufactures provide force-displacement curves in their datasheets. As an example, Figure 1 shows the force-displacement curves of three different types of buttons manufactured by CHERRY Corp [2]. In the following, we will use the term “force graph” to refer to a pair of force-displacement curves for pressing and releasing strokes. As the force graphs show, a physical button provides diverse haptic feedback at different displacement points. The diverse haptic feedback makes users feel depth, repulsive force, and the rigidity of a button while they push or release a button.

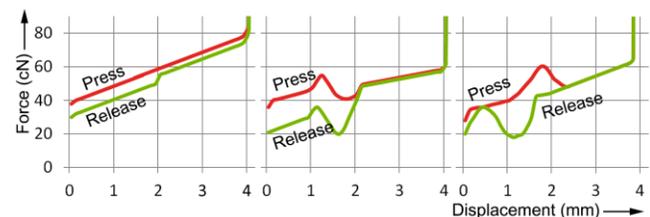


Figure 1. Force graph of variety of physical buttons (CHERRY MX keyswitches [2])

In this paper, we propose a haptic-feedback method for a virtual button, taking into account the entire length of a force-displacement curve, in order to provide haptic feedback throughout the full travel range of a button. We partition the force-displacement curves into a *slope* section, a *jump* section, and a *bottom-out* section, as illustrated in Figure 2, and then, considering the main characteristics for each section, we design the corresponding haptic feedback. For the *slope* region, we adopt the idea of haptic illusion introduced by Kildal [5, 6]. This technique makes possible the sensation of a kinetic movement on a rigid surface and

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uses only vibrotactile stimuli. For the *jump* section and the *bottom-out* section, we use a burst wave whose frequency, duration and envelope are determined on the basis of a force graph; this produces the sensation of a collapse and a collision. In this way, the proposed method provides haptic feedback along the entire length of a force-displacement curve.

We expected that haptic feedback generated by the proposed method would make a virtual button on a touchscreen feel more distinctive and realistic. In order to determine whether this was the case, we conducted two experiments: a pairwise discrimination test between six different types of the virtual buttons and a pairwise matching test between four types of the virtual buttons and their physical counterparts. The experimental results confirmed that the proposed method is effective for generating a variety of discriminable virtual buttons; also, the virtual buttons were realistic enough match physical buttons with a similar force graph.

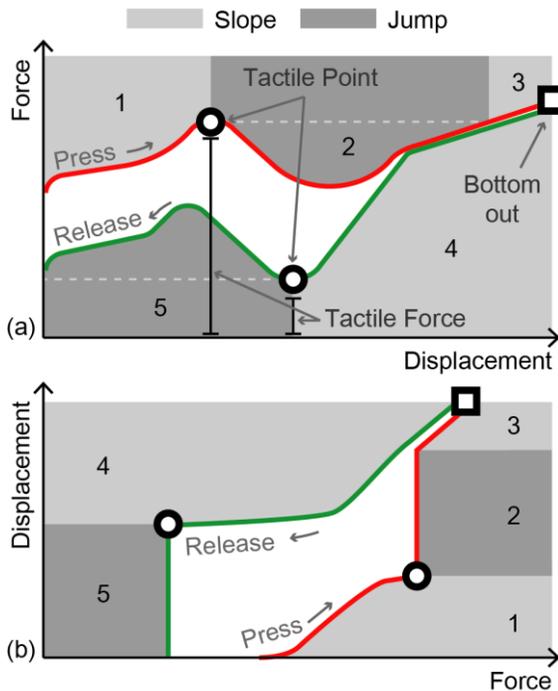


Figure 2. (a) Force-displacement graph of a tactile button
 (b) Displacement-force graph of the same button

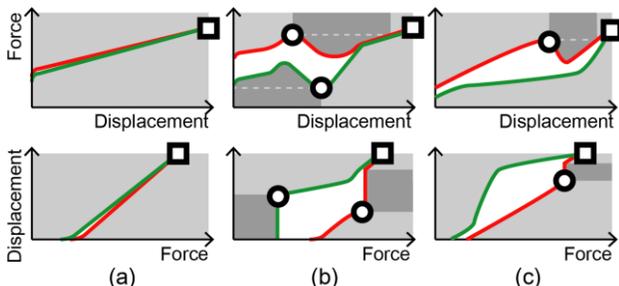


Figure 3. Force graphs of (a) a linear button, and
 (b, c) two different tactile buttons

RELATED WORK

Haptic feedback studies for a virtual button on mobile devices often rely only on tactile feedback [1, 4, 5, 7, 9, 10, 11, 13]. In these studies, various actuators have been tested to generate vibrotactile stimuli, such as eccentric vibration motors [9, 12, 10], electromechanical voice-coil actuators [4, 5, 12], and piezo actuators [1, 7, 9, 11, 13]. After Fukumoto and Sugimura [5] introduced the Active Click concept, a number of studies [1, 9, 11, 13, 12] designed and evaluated various vibrotactile stimuli for a virtual button. The latter mostly examined or compared static and predefined waveforms with various amplitudes, envelopes, frequencies, and durations. In contrast, [3, 10, 15, 16] propose haptic stimuli that are dynamically generated. Nashel and Razzaque [10] designed a virtual button feedback that modulates the frequency of the vibration along with the finger pressure or lingering time. Weiss et al. [16] introduced buttons with adjustable resistances using electromagnet force. In their study, participants could distinguish different buttons with various spring resistances. Doerrer and Werthschuetzky [3] utilized force-displacement curve for a push button simulation; their experimental device can generate force feedback throughout the full range of travel. Similarly, Scilingo et al. [15] used a force-displacement curve to model a simulated softness. These haptic feedback methods [3, 15] are more systematic, in that they are based on force-displacement curves, but they are as yet not applicable to mobile devices because they require a bulky mechanism.

MODELING A BUTTON WITH A FORCE GRAPH

Before we introduce the main idea, we first define and clarify our terminology. Some terms are explained through the illustrations in Figure 2.

- **Press/release curve:** a force-displacement curve for the pressing/releasing stroke.
- **Tactile point:** a local maximum point on a press curve, and a local minimum point on a release curve.
- **Tactile force:** force at a *tactile point*.
- **Jump:** A section of a curve where a sudden displacement occurs. Typically, this appears as a valley after a *tactile point* in force-displacement graph (Figure 2a), and as a vertical line in displacement-force graph (Figure 2b). This sudden displacement accompanies a burst of vibration and a clicking sound.
- **Slope:** the rest section of a curve without *jump*. The curve in this section is monotonically increasing or decreasing. The displacement changes continuously as the force changes.
- **Bottom-out:** a bottom-out occurs when the displacement reaches its maximum travel.

Figure 2 illustrates both the force-displacement graph (Figure 2a) and the corresponding displacement-force (reverse function) graph (Figure 2b) of an abstracted tactile button model. In this graph, a press curve starts with a *slope*

until a *tactile point* (1), followed by a *jump* (2), and then followed by another *slope*, until a *bottom-out* point (3). A release curve starts with a *slope*, until a *tactile point* (4), followed by a *jump* all the way to a complete release (5).

Different physical buttons have different force graphs, as shown in Figure 1 and Figure 3. Their operational characteristics are described in force graphs, which indicate the number and the location of *tactile points* and *jumps*, the gradient of *slopes*, and the magnitude of *tactile force* at *tactile points*. By convention, a button with no *tactile point* is called linear button, and a button with one or more *tactile point* is called tactile button.

DESIGNING VIRTUAL BUTTON FEEDBACK FROM A FORCE GRAPH

In this section, we describe the design of virtual button feedback for each phase of a force graph: *slope*, *jumps* and *bottom-out*. Because of the limitations mentioned in the preceding sections, force feedback devices are not yet applicable to mobile devices. Therefore, we consider using only vibrotactile feedback.

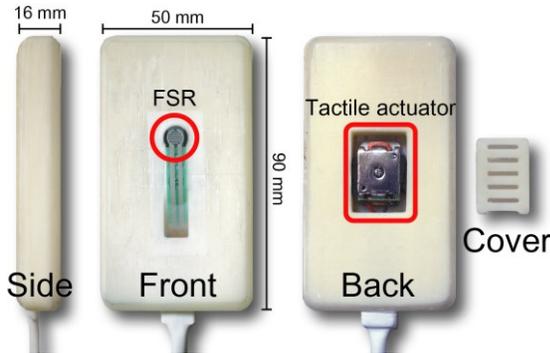


Figure 4. Virtual button feedback device

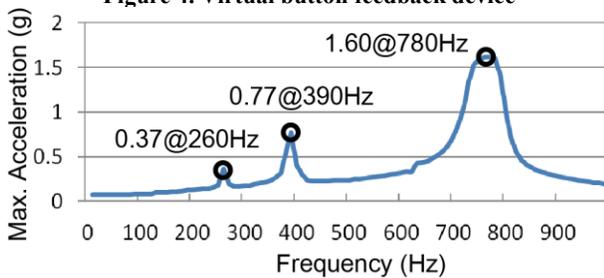


Figure 5. Frequency response of the mobile phone mockup

Apparatus

We implemented a mobile phone mockup that resembles the device in [6]; the implementation consists of a FSR400 force sensor from Interlink Electronics¹ and an electromechanical surface transducer from SparkFun Electronics² (Figure 4). The force sensor was calibrated to measure a normal force on the device, up to 12N. We used a MMA7260Q accelerometer to measure the frequency

¹ <http://www.interlinkelec.co.jp/>

² <https://www.sparkfun.com/products/10917>

response of the actuator (Figure 5). The actuator played a 2V_{pp} sinusoidal waveform at frequencies ranging from 10Hz to 1000Hz. The device resonates at 260Hz, 390Hz, and 780Hz, and the corresponding audible noise, measured 30cm from the device, was 55dB, 60dB, and 95dB, respectively.

The output of the force sensor is transmitted to the PC through a USB 2.0 interface, at a refresh rate of 425Hz. An interface program, implemented in C#, processes sensor data and sends signal messages to a sound synthesizer by UDP packets. The sound synthesizer was implemented with Pure Data³; it dynamically generates a waveform in response to the signal messages. Overall, the mean latency from the force sensor to the vibration transducer was measured and was about 51.12ms (N = 50, SD = 1.65).

Slope Feedback Generation

In the *slope* region, a force change is directly translated to a displacement change. The main challenge here is the mapping between a displacement and a vibrotactile stimulus. Sensing a displacement change is done more by the kinesthetic channel of the body than by the tactile channel. To deal with this problem, Kildal [5, 6] proposed a haptic illusion concept. He implemented an illusory elastic material with a friction grain model. He found that a kinesthetic illusion of compliance can be rendered with a low-latency (~60ms) vibrotactile feedback device.

Following his studies, we implemented a similar friction grain model. As illustrated in Figure 6, when a displacement changes over a grain, it generates a brief burst of vibration – a “grain signal”. A grain signal consists of a 150Hz sinusoidal wave with an inverted saw-tooth envelope. We distributed grain signals evenly along the displacement range (20 grains/mm), and, therefore, a movement along a gentle slope will generate more grain signals, whereas a movement along a stiff slope will generate fewer grain signals. If a new grain signal comes during playing the previous signal, the new one is played immediately. This may cause unwanted high-frequency harmonics; hence, we add a low-pass filter with cutoff frequency of 150Hz at the end of the signal processing steps.

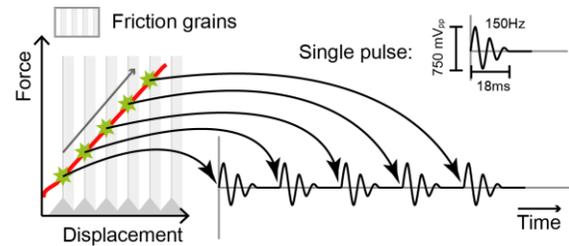


Figure 6. The friction grain model is applied to *slope* feedback generation. When a displacement changes over a grain, a brief burst of vibration is generated.

³ <http://puredata.info/>

Jump Feedback Generation

We designed the haptic feedback for *jump* with a burst sinusoidal wave whose duration and amplitude are determined on the basis of a force graph. *Jump* in a physical button often generates a distinctive vibrotactile feedback. The vibrotactile stimulus for this region has been extensively investigated by previous works [1, 4, 9, 11, 13, 12]. Based on these previous studies, we concluded that a burst of a single signal is sufficient for *jump* feedback.

As illustrated in Figure 7, the duration of the signal is proportional to the change of displacement. This mapping is based on simple common sense: a longer distance takes more time to cross. Further, the amplitude of the signal is proportional to the area between the press or release curve and the horizontal line from the *tactile point*. A broader area means a more abrupt change in force. We reflect this to the intensity of the stimuli. Lastly, the frequency of the signal is predetermined from the resonant frequency of the device, which is 390Hz. This will generate clear amplitude differences from the *slope* signals. For the releasing *jump*, we chose a slightly higher frequency (410Hz), because releasing strokes are often faster than pressing strokes.

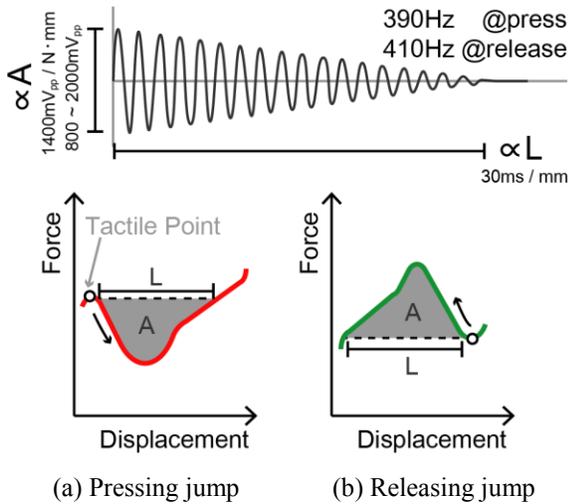


Figure 7. Parameters of *jump* feedback generations

Bottom-out Feedback Generation

Bottom-out is the end point of a button press operation. We designed a *bottom-out* signal with a 200Hz sinusoidal burst with an increasing 30ms saw-tooth envelope (Figure 8). Compared with the *jump* feedback, the frequency here is slightly higher, and the amplitude is increasing instead of decreasing. We chose this vibrotactile feedback design in order to produce a “sudden stop” sensation. The resulting haptic feedback was effective but was not as effective as *slope* feedback or *jump* feedback. Nevertheless, we believe that this is a final touch to complete our haptic feedback design for a virtual button covering the entire length of force-displacement curves.

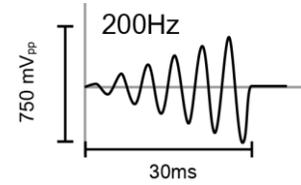


Figure 8. *Bottom-out* feedback

EVALUATION

In order to verify the effectiveness of the proposed haptic feedback design, we asked the two questions:

“Will different force graphs actually generate different and discriminable virtual button sensations?”

“Will people be able to match a virtual button and a physical button if the two have similar force graphs?”

To answer the first question, we designed six different types of virtual buttons and conducted a pairwise discrimination test. To answer the second question, we prepared four different physical buttons, and designed four virtual buttons based on the force graphs of the physical buttons. We then asked participants to find matching virtual and physical button pairs

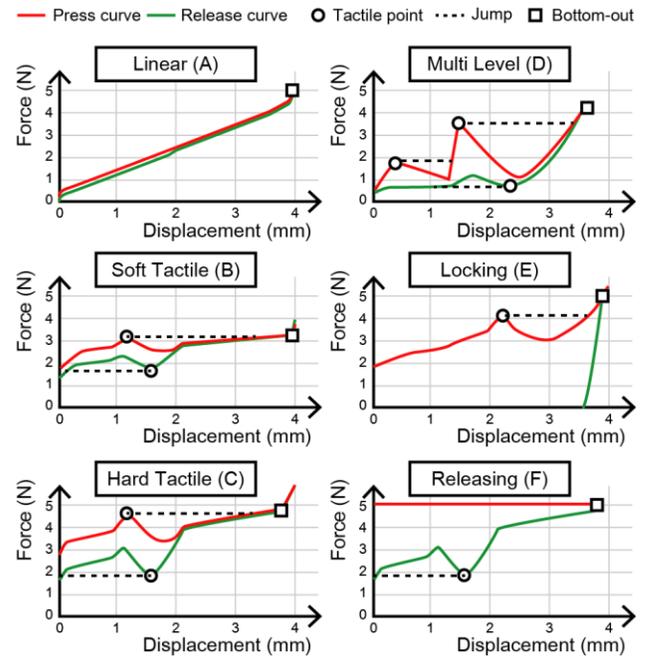


Figure 9. Force graphs of six virtual buttons.

Virtual Button Designs

We designed force graphs for three virtual buttons A~C on the basis of physical buttons from CHERRY Corp [2] and another three virtual buttons D~F on the basis of artificially designed force graphs. Figure 9 shows the force graphs of the six buttons. Button A is a linear switch. Buttons B and C are tactile switches with different *tactile forces*. Button D is a two-level button, such as a camera shutter. Buttons E and F are not actually a separate buttons but represent the

unlocked state and the locked state of a self-locking button. Once a force graph is given, the software module of the previous section generates haptic feedback for a virtual button automatically.

Experiment 1: Discrimination between Virtual Buttons

An ABX test was employed to see how well each pair of different virtual buttons can be distinguished. In each trial, a participant compared three buttons: two different known buttons α and β ⁴ and one unknown button X that is randomly selected from α and β . We informed participants that α and β were different, but did not tell them what button (A~F) is assigned. Participants were asked whether $\alpha = X$ or $\beta = X$. We made a list of 15 pairs out of six buttons, multiplied that number by ten, and then shuffled the list of 150 pairs to generate a test set for a participant. As a result, each participant tested each pair ten times. In this test, a participant is considered to be able to discriminate between two buttons when there is at most one error in ten trials ($p < 0.05$).

Group \ Measure	Normal	Noisy
Avg. time (SD)	20.9 min (6.2)	23.3 min (8.4)
Aggregated Errors / Trials	8 / 1350 (0.59%)	46 / 1350 (3.41%)
ABX test result # Fails / Total	1 / 135 (0.74%)	8 / 135 (5.93%)

Table 1. Summary of the test result (10 trials per one ABX test)

	(a) Normal group					(b) Noisy group				
	A	B	C	D	E	A	B	C	D	E
B	0					3				
C	1	0				2	5			
D	0	0	2			1	3	10		
E	0	0	1	1		0	4	5	5	
F	1	2	0	0	0	1	4	1	0	2

Table 2. Total discrimination errors by all participants

White: no participant failed the ABX test
 Light gray: one participant failed the ABX test
 Dark gray: two participants failed the ABX test

Because the mockup device makes an audible sound, we divided participants into *Normal* and *Noisy* group. *Normal* group performed the tests in a quiet and calm environment. In contrast, *Noisy* group wore 3M earplugs and Bose QC15 noise-cancelling headphones playing an ambient raining sound⁵ to block the sound generated by the mockup. We recruited nine participants (Ages from 20 to 27 (avg = 23.4), 7 Males and 2 Females) for *Normal* group, and another nine

⁴ Conventionally, stimuli labels of ABX test is named A, B, and X. However, we use α , β , and X here to avoid confusion with virtual button labels from A to F.

⁵ <http://www.rainymood.com>

participants (Ages from 18 to 26 (avg = 22.7), 7 Male and 2 Females) for *Noisy* group. Participants were undergraduate or graduate students. All were right-handed they performed the tests with their right hands. Before the test, they tried every feedback freely, for about 3 minutes.

Table 1 and Table 2 show the results of the ABX test. The gray boxes in Table 2 indicate that at least one participant failed the ABX test with given pairs of virtual buttons. *Noisy* group clearly showed more errors, and the most confused pair was C-D. In this case, the first *jump* of button D tends to be masked by the more intensive second *jump*, and therefore button C and D generate similar feedback signals. Nevertheless, even in the worst case, seven out of nine participants could successfully discriminate between two different buttons.

Experiment 2: Matching Physical and Virtual Buttons

Buttons A, B, and C are generated on the basis of datasheets of real physical buttons. The self-locking button (EF) also resembles a real self-locking button, although we could not find a datasheet for it. For this button, we present E and F alternately. Thus, we had four virtual buttons with physical button counterparts. The mapping between the two sets is shown in Table 3.

A	CHERRY Corp. MX switch black (linear type, Figure 1-left)
B	CHERRY Corp. MX switch brown (tactile type, 55cN tactile force, Figure 1-middle)
C	CHERRY Corp. MX switch white (tactile type, 65cN tactile force)
EF	ALPS Electronics, self-locking switch (extracted from Apple Extended Keyboard II ⁶)

Table 3. Four virtual buttons and their physical button counterparts. EF means that the feedback is alternating between E and F at each button actuation.

Without giving them any additional information about the buttons, we asked the participants to find equivalent virtual and physical button pairs. Participants were allowed to freely try four virtual buttons and four physical buttons during the experiment. The 18 participants of Experiment 1 participated again in this experiment. The matching task took about 5 minutes for each participant.

Nine participants could make perfect matches between virtual and physical buttons. Of the other participants, three participants swapped C and EF, another three participants swapped B and C, one participant swapped A and B, and two participants were confused between three buttons. Overall, the participants correctly matched 79.2% (76 correct matches per 96 trials) of a given virtual button. In

⁶ This keyboard was manufactured in early 1990s. ALPS Electronics no more produces keyboard switches now.

addition, after we gave the right answers, with short explanations, most participants agreed with the mappings between the virtual and physical buttons.

Post-Experiment Interview

After participants performed two experiments, we asked them to enunciate, in natural language, what they felt of the virtual buttons. Almost all reported a button-like sensation for buttons **B**, **C** and **D**, all of which have distinctive *tactile points* on both press and release curves. Fifteen participants reported a smooth feeling on button **A**, but three participants disliked its uncertain operational feel. Four participants reported unpleasant feelings on button **E**, because it does not provide any tactile feedback during a releasing stroke, and, for similar reason, nine participants considered button **F** is unpleasant. Some participants had a favorite button: three picked button **A**, two picked button **B**, five picked button **C**, and one picked button. In summary, participants could feel and report rich and diverse haptic sensations when playing with the virtual buttons in the experiments. Their preferences varied from person to person.

CONCLUSION AND FUTURE WORK

We proposed a haptic feedback method for a virtual button based on the force graph of a physical button. The distinguishing feature of the proposed method is that it provides haptic feedback not only for the *jump* section but also for the *slope* sections before the *jump* section in the force graph. We conducted two user experiments to show that the resultant haptic feedback is realistic and distinctive. In the first experiment, participants were able to distinguish six different virtual buttons quite successfully. The confusion rate was about 5.9% in a noisy environment and less than 1% in a quiet environment. In the second experiment, participants were able to associate four virtual buttons with their physical counterparts at a correct answer rate of 79.2%.

The main contribution of the current study is that it was an original attempt to enhance the haptic feedback of a virtual button by providing vibrotactile feedback along the entire length of a force-displacement curve. Experimental results show that the proposed method is indeed effective.

Another contribution of the current study is that it provides a systematic design-method for virtual button haptic feedback on the basis of a force graph. In other words, the design of haptic feedback for a virtual button can be done almost mechanically given the force graph of a physical button counterpart. This design method will enable haptic feedback design for a virtual button to be based solidly on our existing knowledge of physical buttons.

A shortcoming of the current study is the lack of comparison with a base case, e.g., the case of click-only feedback. The current haptic feedback design is clearly

richer than that of the base case, but we are yet to determine if it will be really more distinguishable and realistic. The first task in a future study is a more rigorous evaluation of the proposed haptic feedback method in comparison with other options.

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REFERENCES

- Chen, H.-Y., Park, J., Dai, S., and Tan, H. Design and evaluation of identifiable key-click signals for mobile devices. *Haptics, IEEE Transactions on* 4, 4 (2011), 229–241.
- CHERRY Corporation. MX series keyswitches. <http://www.cherrycorp.com/english/switches/key/mx.htm>.
- Doerrer, C., and Werthschuetzky, R. Simulating push-buttons using a haptic display: Requirements on force resolution and force-displacement curve. *EuroHaptics 2002*.
- Fukumoto, M., and Sugimura, T. Active click: tactile feedback for touch panels. *CHI 2001 Extended Abstracts*.
- Kildal, J. 3d-press: haptic illusion of compliance when pressing on a rigid surface. *ICMI-MLMI 2010*.
- Kildal, J. Kooboh: Variable tangible properties in a handheld haptic-illusion box. *Haptics: Perception, Devices, Mobility, and Communication*, vol. 7283. Springer, 2012, 191–194.
- Kim, J., Dai, X., Cao, X., Picciotto, C., Tan, D., and Tan, H. A masking study of key-click feedback signals on a virtual keyboard. *Haptics: Perception, Devices, Mobility, and Communication*, vol. 7282. Springer, 2012, 247–257.
- Koskinen, E. *Optimizing tactile feedback for virtual buttons in mobile devices*. PhD thesis, Helsinki University of Technology, 2008.
- Koskinen, E., Kaaresoja, T., and Laitinen, P. Feel-good touch: finding the most pleasant tactile feedback for a mobile touch screen button. *ICMI 2008*.
- Nashel, A., and Razzaque, S. Tactile virtual buttons for mobile devices. *CHI 2003 Extended Abstracts*.
- Pakkanen, T., Raisamo, R., Raisamo, J., Salminen, K., and Surakka, V. Comparison of three designs for haptic button edges on touchscreens. *Haptics Symposium*, IEEE (2010).
- Park, G., Choi, S., Hwang, K., Kim, S., Sa, J., and Joung, M. Tactile effect design and evaluation for virtual buttons on a mobile device touchscreen. *MobileHCI 2011*.
- Poupyrev, I., and Maruyama, S. Tactile interfaces for small touch screens. *UIST 2003*.
- Poupyrev, I., Maruyama, S., and Rekimoto, J. Ambient touch: designing tactile interfaces for handheld devices. *UIST 2002*.
- Scilingo, E., Bianchi, M., Grioli, G., and Bicchi, A. Rendering softness: Integration of kinesthetic and cutaneous information in a haptic device. *Haptics, IEEE Transactions on* 3, 2 (2010), 109–118.
- Weiss, M., Remy, C., and Borchers, J. Rendering physical effects in tabletop controls. *CHI 2011*.