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Localized Rendering of Button Click Sensation via Active Lateral Force Feedback

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Abstract— **We have developed a novel button click rendering mechanism based on active lateral force feedback. The effect can be localized because electroadhesion between a finger and a surface can be localized. We did psychophysical experiments to evaluate the quality of a rendered button click, which subjects judged to be acceptable. We can thus generate a button click on a flat surface without macroscopic motion of the surface in the lateral or normal direction, and we can localize this haptic effect to an individual finger. This mechanism is promising for touch-typing keyboard rendering ("multi-click").**

I. INTRODUCTION

Professional tablets and two-in-ones (such as the Microsoft Surface) are growing in popularity at the expense of traditional laptop computers. Laptops, however, offer a key advantage: keyboards that enable touch-typing in which at least some of the fingertips rest on the keys. Keys are activated by force rather than by contact. At present, touch-typing remains one of the highest-bandwidth means of communicating information from a human to a computer. Keyboards, however, take up space that often goes unused; as such, an exciting development would be a touchscreen keyboard that supported touch-typing. Requirements for such a device would include localized pressure sensing, tactile feedback, and mechanical simplicity (e.g., few moving parts).

Many researchers have studied how to render a button click sensation. Fukumoto et al. and Chen et al. used vibrations with a sinusoidal waveform to simulate the click sensation [1], [2]. Unlike physical buttons, the vibrotactile display cannot provide continuous contact force, leading to the lack of a realistic key-click sensation [3], [4].

Monnoyer et al. and Tashiro et al. [5], [6] used ultrasonic vibrations to modulate the friction between the fingertip and surface. They showed that some people could feel a click sensation if a transition from high friction to low friction occurred as the finger pushed on the surface; however, the sensation depended on the impedance of each individual's fingertip. More generally, it is difficult to generate strong haptic effects via friction modulation unless the finger and surface are sliding relative to one another in the lateral direction [6].

Zoller et al. used a thin electromagnetic actuator module on a capacitive touchscreen to provide push button feedback [7]. Similarly, a commercial force touch trackpad (MacBook Pro Retina 2015, Apple) employed an electromagnetic linear actuator to provide click feedback [8]. These methods, however, make no attempt to localize the click sensation: all fingers touching the surface will feel the same click.

To provide localized control of haptic effects, Hudin and colleagues proposed a time-reversal wave focusing method which could be used to create high amplitude ultrasonic vibration at localized points on the surface [9]. A finger placed over one of these points would be "ejected" (thrown off the surface), which was easily perceived. This method, although elegant, provided very little control over the waveform applied to the finger, and also produced an undesirable audible artifact. In subsequent work, Hudin proposed another method called non-radiating ultrasonic vibrations [10] and demonstrated independent control of the ultrasonic vibration at different positions on a surface by using two piezoelectric actuators. Even though the non-radiating ultrasonic vibration method is able to localize friction modulation, the vibration fields are wholly dependent on the position of the actuators. Thus, it is difficult for this method to localize friction modulation at more than a few point on the surface.

Extending our previous work (the UltraShiver [11]), this paper proposes a novel method for rendering a localized button click sensation. In this paper, the ability of the UltraShiver to localize control of the active lateral force on the fingertip is demonstrated. The carrier displacements in the lateral and normal directions are then measured to exhibit that the normal oscillation of the UltraShiver has little effect on the perception of button click rendering. Further, the force profile of pressing on the virtual button is measured to show the robust control of the UltraShiver for button click rendering. Finally, perceptual experiments are conducted to analyze the quality of button click rendering and investigate the possible relation between the parameters of the stimuli. Overall, the UltraShiver not only simulates the button click sensation but also localizes the effect, presenting a promising method for virtual keyboard rendering.

II. BACKGROUND OF ULTRASHIVER

The new method presented here is based on a lateral force feedback device, the UltraShiver, which we presented in a previous study [11]. The UltraShiver consists of two piezoelectric actuators and a sheet of anodized aluminum (shown in figure 1). The lateral force generation of the UltraShiver depends on synchronization of in-plane ultrasonic oscillation and out-of-plane electroadhesive forces. The in-plane ultrasonic oscillation is due to the longitudinal resonance of the UltraShiver and is excited by two piezos.

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The out-of-plane electroadhesive force is controlled by an electric current applied between the fingertip and the surface of the anodized aluminum. By adjusting the phase between the ultrasonic oscillation and the electroadhesive force, the direction and magnitude of the lateral force can be controlled.

III. METHOD AND EXPERIMENTS

Three experiments were performed to study the utility of the UltraShiver as a means of creating and localizing a button click sensation. Experiment 1 focused on isolation: the ability of the UltraShiver to localize lateral force to a single finger. Experiment 2 measured the carrier displacements in both the lateral and normal directions and the force generating capacities of the UltraShiver for rendering the button click sensation. Experiment 3 investigated subjects' perception of the rendered button clicks.

Experiment 1 and Experiment 2 shared most parts of the setup (in figure 1 and figure 2), except for the position of a Laser Doppler Vibrometer (LDV), the number of involved fingers, and finger movement constraints. As shown in figure 1 and figure 2, the UltraShiver was mounted to an acrylic block with six brass flexures. The acrylic block was fixed on a six-axis force sensor (ATI17 Nano load cell), which was used to measure the normal and lateral force. The piezoelectric actuators were controlled with a custom amplifier, and the electroadhesive current was adjusted with a custom high voltage source (more details are reported in [11]).

A. Setup in Experiment 1

The LDV (CLV-700, Polytec,Inc) was used to measure the lateral velocity of the fingers. The index finger and the middle finger of the dominant hand were used in Experiment 1. One of the two fingers was randomly chosen to wear a finger cot, which was used to electrically insulate the finger. Finger movement was not constrained in Experiment 1. The electrically grounded fingers lightly touched the surface. Since we had only one LDV, it was repositioned in separate trials to measure the lateral velocity of the each finger. All signals were recorded using a NI USB-6361 Multifunctional I/O Device with a 1 MHz sampling frequency.

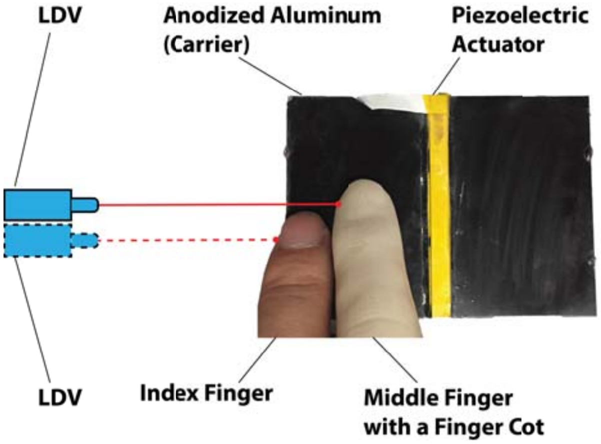

Fig. 1. Top view of the setup in Experiment 1.

B. Setup in Experiment 2

The LDV was used to measure the carrier velocity in the lateral and normal directions. A 45° mirror as seen in figure 2 was used to simplify the LDV mounting. The index finger of the dominant hand was used in Experiment 2. The finger was constrained to move only up and down. The electrically grounded finger lightly pressed the surface. Since there was only one LDV in the experiments, the position of the LDV was adjusted between trials to measure both the lateral velocity and normal velocity of the surface. All signals were recorded using a NI USB-6361 Multifunctional I/O Device with a 300 kHz sampling frequency.

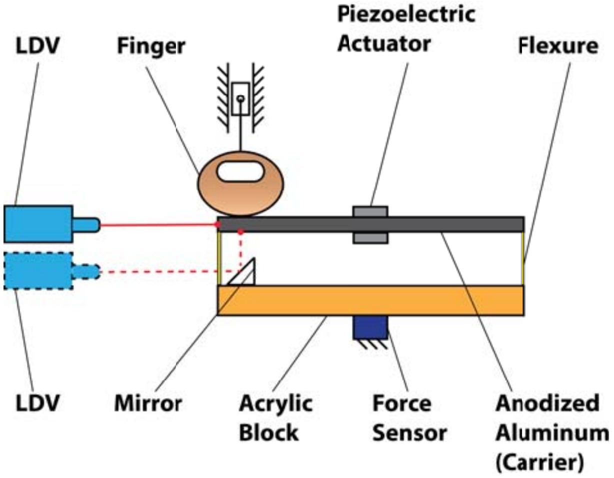

Fig. 2. Side view of the setup in Experiment 2.

C. Experiment 1: Localized Control of Lateral Force

The ability of the UltraShiver to localize control of the lateral force was investigated in terms of both lateral force generation on the fingertip and vibration propagation between the fingers. Experiment 1 was designed to investigate the latter topic by attempting to avoid lateral force on one of two fingers, both of which were touching the surface. This raised the question of how to localize lateral force. In principle, the UltraShiver should not produce lateral force if either the ultrasonic oscillation or the electroadhesive force is absent. Localizing ultrasonic oscillation is difficult while localizing electroadhesion is easier. For instance, one approach is to etch the conductive layer of the surface into a grid, each section of which is individually connected to its own electroadhesion high voltage source. Our prototype of the UltraShiver however used a single sheet of anodized aluminum with isotropic electrical conductivity, so a finger cot was used to electrically insulate one fingertip from the surface and thereby localize the electroadhesive force to the other finger.

During the experiment, the frequency of the electroadhesion voltage was set to 10 Hz less than that of the piezoelectric voltage, so that the lateral force on the fingertip varied at 10 Hz beat frequency (more details are reported in [11]). Measurements of the lateral velocity of the fingers were used to investigate whether there was a lateral force generated on the finger. The measurement points of the LDV were on the left sides of the fingers and close to the contact patch area between the fingertip and the surface (in figure 1). Each measurement lasted 2 seconds and was repeated five times. Due to differences in contact patch areas, both mechanical and electrical properties of fingers could affect the lateral force on the fingertip. For this reason, either the index finger or the middle finger was randomly chosen to wear the finger cot during each measurement.

D. Experiment 2: Rendering of Button Click Sensation

1) Preliminary Experiment: Carrier Velocity Measurement: In this paper, we claim that our method of button click rendering is based on lateral force feedback. However, the UltraShiver exhibits ultrasonic oscillations in both the lateral and normal directions [11]. In preliminary experiments, we measured the carrier velocity in both directions to determine whether ultrasonic oscillation in the normal direction could affect the perception of button clicks.

During the experiments, the index finger of the dominant hand could only move up and down and press on the surface (in figure 2). While the finger pressed on the surface, the carrier velocity was measured by the LDV. Since we had only one LDV, the carrier velocities in the lateral and normal directions were measured in separate trials. Each measurement lasted 5 seconds.

2) Button Click Rendering Algorithm: The button click rendering algorithm was based on modulation of the active lateral force on the fingertip which was achieved by adjusting the phase between the ultrasonic oscillation and the electroadhesive voltage (0°: move finger to the left; 180°: move finger to the right). Note that ultrasonic oscillations were operating at all times so as to avoid perceptual artifacts. When the pressing (normal) force crossed over a set threshold, a square-waveform lateral force was constructed and applied to the fingertip (see the command signal in figure 6). The normal force threshold was 600 mN, a typical value taken from the measurement of a physical button (Logitech Keyboard K120). By varying the duration and duty cycle of the square waveform, the tactile characteristics of the rendered button click could be changed over a fairly broad range (more details in section III-E).

3) Force Profile of Button Click Rendering Experiment: During these experiments, the index finger of the dominant hand could move only up and down (in figure 2). Subjects were asked to press on the surface and then lift up, as if pressing on a physical button. When the pressing force reached the set threshold (600 mN), the stimulus of button click rendering was applied to the finger. The lateral and normal forces were measured by the six-axis force sensor. There were fifteen trials in the experiment. During each trial, the subjects pressed with the same amount of force, to the best of their ability.

It should be noted that only one subject (Author Heng Xu) participated in experiments 1 and 2.

E. Experiment 3: Perceptual Experiment Protocol

Perceptual experiments were designed to evaluate the quality and variety of the rendered button clicks that resulted in user acceptance.

1) Participants: Ten subjects (20 to 30 years of age, one left-handed, four female) participated in this experiment. Seven of the subjects were naive to the purpose of the experiment and had no experience with surface haptics, while the other three subjects were graduate students in the haptics group. The authors did not serve as subjects in this experiment. Subject participation was approved by the Northwestern Institutional Review Board, subjects gave informed consent, and subjects were paid for their time.

2) Experiment Protocol: Each stimulus consisted of one cycle of a square waveform. The parameters of duty cycle and duration of the stimulus were adjusted to generate different button clicks (see the command signal in figure 6). The duty cycle was defined as a ratio of the duration with positive lateral force to the total duration of the stimulus. The duty cycle was one of three levels: 5%, 25%, or 50%. The duration was one of 26 levels, ranging from 1 millisecond to 251 milliseconds with equal intervals between levels.

There were six blocks in the experiment. Each block employed a duty cycle from one of the three levels (5%, 25%, or 50%), and swept through the duration levels along either an increasing or decreasing trajectory. The increasing trajectory meant that the duration started with the minimum value (1 millisecond) and increased to the maximum value (251 milliseconds) across 26 successive stimuli. The decreasing trajectory was the reverse. Thus, each stimulus with the same duration and duty cycle was presented twice, once in each sweep direction. Each block took around 5 minutes, and the total experiment lasted 30 - 40 minutes, including breaks.

Before starting the experiment, subjects were asked to wash and dry their hands. They were exposed to samples of rendered button clicks and familiarized with the experimental platform. During each block, subjects were asked to press on the surface with the index finger of their dominant hand, as if pressing on a physical button. They were further instructed to consistently press on the same contact patch area of the surface with a constant contact angle between the finger and the surface. Headphones playing pink noise were worn to cancel any sounds produced by the experimental platform. A yellow LED indicated whether the subject reached the normal force threshold of the button click.

After each trial, subjects were asked whether the stimulus felt like an acceptable button click, and gave YES or NO verbal answers that were recorded by the experimenter. Subjects made their judgment based on their own prior experience with buttons.

3) Data Analysis: For each subject, the first YES answer and the last YES answer were used to define the boundaries of the good-button range for each duty cycle. These boundaries were averaged over the increasing trajectory and the decreasing trajectory.

IV. RESULTS

A. Experiment 1: Localized Control of Lateral Force

Figures 3 and 4 show the lateral displacement envelope (at 10 Hz) of the index finger and the middle finger. When the middle finger wears a finger cot, the lateral displacement of the index finger is in the range of 550 to 600 μm, and the lateral displacement of the middle finger is below 30 μm (in figure 3). When the index finger wears a finger cot, the lateral displacement of the middle finger is in the range of 330 to 470 μm, and the lateral displacement of the index finger is below 12 μm (in figure 4). These isolation results confirm good localization of the lateral force effects.

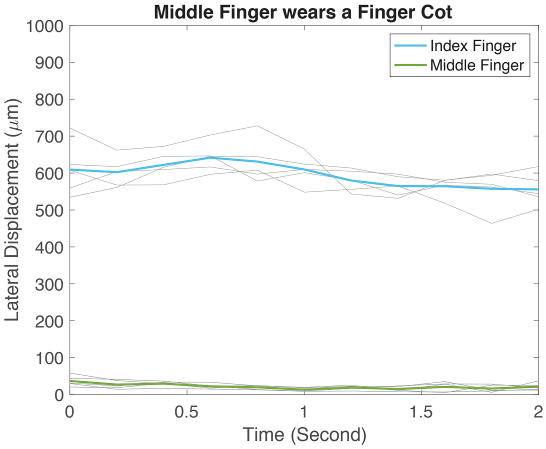

Fig. 3. Lateral displacement envelope of the index finger and the middle finger when the middle finger wears a finger cot. The blue curve is the average displacement envelope of the index finger over five trials. The green curve is the average displacement envelope of the middle finger over five trials.

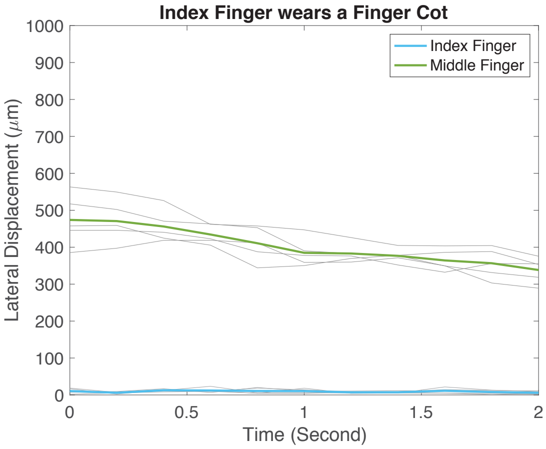

Fig. 4. Lateral displacement envelope of the index finger and the middle finger when the index finger wears a finger cot. The blue curve is the average displacement envelope of the index finger over five trials. The green curve is the average displacement envelope of the middle finger over five trials.

B. Experiment 2: Carrier Displacement Measurement

Figure 5 shows the lateral and normal displacement of the carrier when the finger repeatedly presses on the surface and lifts up over the course of five seconds. Since the normal and lateral measurements were made on separate trials, the pressing events do not align. With no finger touching the surface, the lateral and normal displacements of the surface are around 5.6 μm and 0.035 μm (at 30 kHz). With the finger pressing on the surface, the lateral displacement decreases to around 5 μm, and the normal displacement increases to around 0.065 μm.

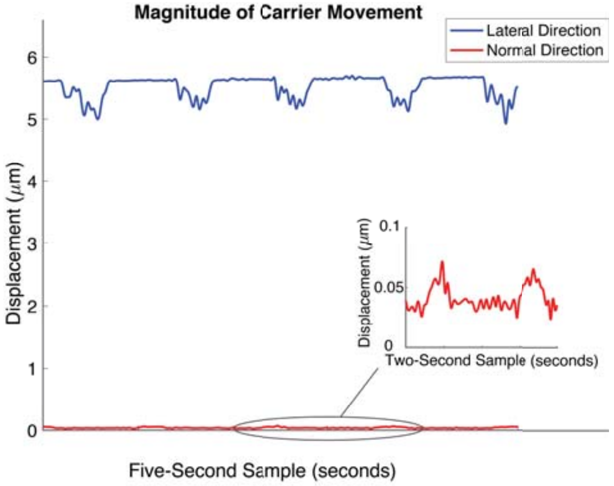

Fig. 5. Data samples showing the magnitude of the carrier displacement in the lateral and normal directions when the finger repeatedly presses on the surface and lifts up.

C. Experiment 2: Force Profile of Button Click Rendering

Figures 6 and 7 show the force profile of the finger during button click rendering. Based on the change of the normal force (in figure 7), the pressing action starts around 0.26 seconds and lasts 0.44 seconds. The average pressing force is around 900 mN. The command signal is a 160 millisecond square waveform with a 25% duty cycle and 500 mN peak-to-peak magnitude.

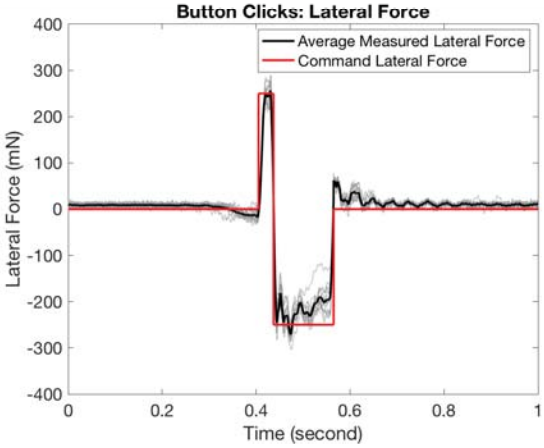

Fig. 6. Lateral force measurement during button click rendering. The gray curves are recorded across fifteen trials. The black curve is the average measured lateral force of the fifteen trials. The red curve is the target of this rendering.

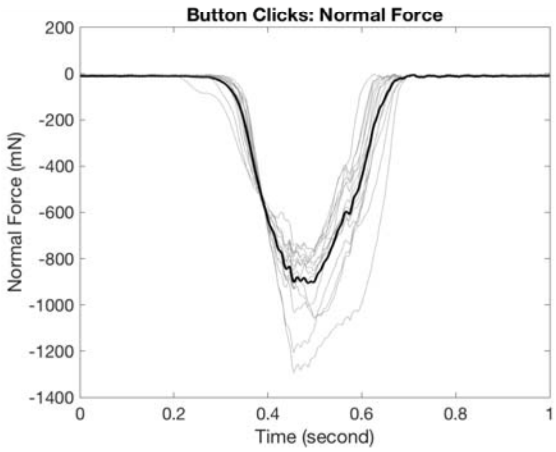

Fig. 7. Normal force measurement during button click rendering. The gray curves are recorded in fifteen trials. The black curve is the average of the fifteen trials.

D. Experiment 3: Perceptual Experiment

Figure 8 shows the range of stimulus durations that are judged to be acceptable button clicks. There are three different duty cycles: 5%, 25%, and 50%. For the 5% duty cycle, the good-button range of the duration is from 14.4 ± 14.4 milliseconds to 172.1 ± 24.18 milliseconds. For the 25% duty cycle, the good-button range of the duration is from 11.3 ± 7.7 milliseconds to 106.8 ± 30.4 milliseconds. For the 50% duty cycle, the good-button range of the duration is from 6.5 ± 1.6 milliseconds to 52.8 ± 17.45 milliseconds.

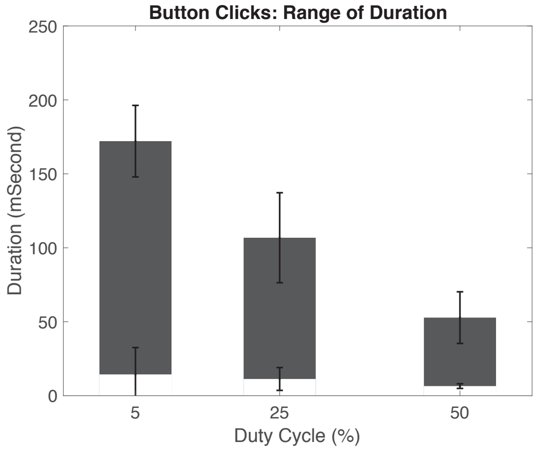

Fig. 8. The average range of stimulus durations which are judged to be acceptable button clicks for different duty cycles. The error bars are the standard deviations of the ranges over ten subjects.

V. DISCUSSION

A. Localized Control of Lateral Force

Since a low-frequency stimulus was used in the button click rendering algorithm, the Meissner corpuscle is expected to dominate the touch sensation. The human detection threshold of vibration as a function of frequency has been previously addressed in the literature [12]–[14]. Vibrations of 100 μm are enough to stimulate a Meissner corpuscle at 10 Hz. As the frequency of vibrations decreases, the human detection threshold increases.

The lateral displacement data in figures 3 and 4 show that around 5% of the vibration amplitude of the bare finger is propagated to the finger wearing a finger cot via the surface or the skeleton of the hand. Since the vibration magnitude of the finger wearing a finger cot is lower than the detection threshold, this finger presumably cannot feel the vibration. The implication is that the UltraShiver can localize control the lateral force on the finger based on localized control of electroadhesion between the finger and the surface.

Since the ultrasonic oscillation of the surface is not uniform, the region of the surface closer to the center has a lower oscillation velocity. For this reason, the lateral displacement of the middle finger in figure 4 is lower than that of the index finger in figure 3 (more details are reported in [11]).

B. Carrier Displacement Measurement

A comparison between data in figure 5 shows that the magnitude of the normal displacement is less than 1% of the magnitude of the lateral displacement. The oscillating energy of the surface is mostly stored in lateral motion. As the finger presses on the surface, some portion of the oscillating energy propagates into the fingertip, thus decreasing the magnitude of the lateral oscillation.

When the fingertip presses on the surface, changes of the mode shape of the oscillating surface may significantly affect the magnitude of the normal oscillation. That could be a reason why the magnitude of the normal displacement increases with finger pressure. Alternatively, the increased magnitude of the normal oscillation could be due to a decrease in lateral oscillation energy: that decrease would transfer energy to the finger and also increase normal oscillation. Compared with the change in the lateral displacement, the change in the normal displacement will have less effect on the perception of button click rendering due to its small amplitude.

C. Force Profile of Button Click Rendering

Figure 7 shows the normal force profile during pressing. The curves have been aligned at (0.4sec, 600 mN), which is when the lateral force is triggered. The measured square-waveform lateral force applied to the finger (the gray curves in figure 6) is closely matched with the command signal, suggesting that the UltraShiver can control the active lateral force and execute the button click rendering algorithm with great precision.

D. Perceptual Experiment

As the duty cycle of the stimuli increased from 5% to 50%, the duration judged as having a good button feeling decreased from 157.7 milliseconds to 46.3 milliseconds. Subjects preferred a short stimulus at a large duty cycle. In addition, some subjects reported that they perceived an oscillation rather than a click when the stimulus had a long duration at the 50% duty cycle.

Thus, we propose a hypothesis: the quality of button click rendering is related to the number of events perceived in the stimulus, and the detection of only one event is judged to be an acceptable button click.

To evaluate the hypothesis, it is useful to calculate the width of the shortest acceptable pulse for the different duty cycles as the product of the minimal duration rated good and the duty cycle of the stimulus (in figure 9). The hypothesis that this shortest acceptable pulse is the boundary for detecting one click event is supported by the finding that the values for the 25% and 50% duty cycles are quite similar (26.7 ± 7.6 milliseconds vs. 26.4 ± 8.7 milliseconds). The value of 26.4 milliseconds may be a threshold for detecting a single stimulus event. In comparison, however, the shortest acceptable pulse width at the 5% duty cycle is lower (8.6 ± 1.2 milliseconds). For the 5% duty cycle, the long pulse width may be too long to render an acceptable button click, while at the short pulse width the subjects may be able to detect only one event across the entire cycle rather than in the shorter part of the pulse.

In addition to the results in the perceptual experiments, all subjects told the experimenter that they could clearly perceive some type of click sensation among all the stimuli. One subject reported that some rendered click sensations felt better than commercial click rendering (Dell trackpad).

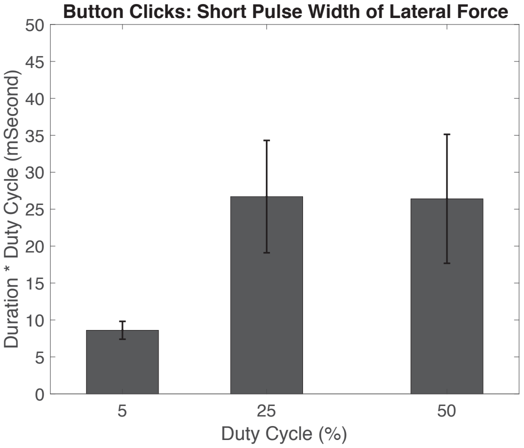

Fig. 9. Short pulse width: product of the duration and the duty cycle of the stimuli. The error bars are the standard deviations of the Short pulse widths over ten subjects.

VI. CONCLUSION

The contributions of this study are demonstrating an ability to localize control of an active lateral force, and proposing a convincing button click rendering mechanism based on active lateral force. These two results suggest that the Ultrashiver is a good candidate for virtual keyboard rendering.

ACKNOWLEDGMENT

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