Effect of Electrostatic Tactile Feedback on Accuracy and Efficiency of Pan Gestures on Touch Screens

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Abstract—Recently, many studies examined electrostatic tactile feedback on touch screens to enrich interaction experience. However, it is unclear as to whether added tactile feedback during a sliding process increases the accuracy of pan gestures with velocity constraints. In this study, a custom-designed electrostatic tactile display was considered. Initially, the accuracy and efficiency of pan gestures were compared under two conditions, namely with and without electrostatic tactile feedback. This was followed by exploring the evolution of completion time (CT) with different indices of difficulties (ID). Experimental results with 12 participants indicated that the accuracy and completion time of pan gestures with added tactile feedback significantly exceeded those without tactile feedback. Furthermore, the relationship between CT and ID satisfied Fitts' Law with a correlation coefficient exceeding 0.9. Based on the findings, a "Tactile Fruit Sorting" game was designed, and subjective and objective evaluations were conducted. The results confirmed that the added tactile feedback enhanced both user performance and interest with respect to the game.

Index Terms—Tactile feedback, electrostatic, index of difficulties, pan gestures, accuracy, completion time

1 Introduction

Touch screens including mobile phones, tablet devices and ATM terminals are prevalent in everyday life. The success of touch screens relies on several interaction characteristics, including intuitive command input through direct touch and immediate feedback/output through visual and/or auditory channels. Over the last two decades, previous studies examined tactile feedback with the aim of enriching interaction experiences based on touch screens. However, most studies on touch screens focused on displaying physical properties, such as textures, of an image through added tactile feedback capability [1], [2], [3]. In addition to this dominant paradigm of using tactile feedback, it is necessary to explore other methods of using tactile feedback with touch screens.

The aim of the present study involves analyzing the manner in which added electrostatic tactile feedback influences accuracy and efficiency of pan gestures. Specifically, the study examined the effect of a spring-like linear friction force on pan gestures. It is expected that this knowledge contributes to the creation of a few novel interaction paradigms for touch screens, such as tactile-enhanced pan gestures, by fully utilizing added tactile feedback.

Typical gestures, such as pan, pinch and spread gestures, provide a convenient way to interact with a touch screen. Unfortunately, users only obtain feedback information through visual and/or audio channels, and this limits the richness of interaction experience during the finger movement process. If users are able to feel varied physical sensations during the movement process, then they can obtain more interest and engagement during the interaction. For example, during a pan gesture, users can feel the frictional experience of sliding along the surfaces of different materials such as wood or ice. This versatile user experience can be useful for novel games or for educational purposes.

Given the benefits of more diverse sensations during the gesture movement process, it is necessary to ensure that the accuracy and efficiency of gestures is not degraded by added tactile feedback. To the best of the authors' knowledge, it is unclear as to whether added friction feedback during the sliding process assists or degrades the accuracy and speed of pan gestures.

The contributions of this paper are: as follows:

1. A custom-designed electrostatic tactile display was used to explore the variations in accuracy and efficiency under two conditions as to whether electrostatic tactile feedback is utilized on a touch screen. The experimental results with twelve participants illustrate that the accuracy and completion time (CT) of pan gestures with the added tactile feedback significantly exceed those without tactile feedback.

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2. The added electrostatic tactile feedback was used to explore the manner in which the completion time (CT) of pan gestures evolves with different indices of difficulties (ID). The experimental results indicate that the relationship between CT and ID satisfies Fitts' Law, and the related correlation coefficient is higher than 0.9.
3. A "Tactile Fruit Sorting" game was designed to illustrate the benefits of tactile-enhanced pan gestures. Both subjective and objective evaluations indicate that the added electrostatic tactile feedback improves players' performance and enhances users' interest in the game.

2 Related Works

Tactile feedback on the screen of a tablet is produced by three approaches, namely mechanical vibration [5], [6], [7], [8], [9], squeezing air-film effect by piezoelectric vibration [10], [11], [12], [13], [14], and electrostatic tactile feedback [4], [15]. The first approach is unable to produce fine detailed tactile sensations such as textures or the varied friction patterns. The second approach produces a lower friction level on a tablet when compared to those of its original materials such as a glass plate or an aluminum plate. The third approach produces a higher friction level when compared to that of the original material of a tablet.

The effect of tactile feedback on typical gestures was studied by a few pioneering studies. Casiez et al. [16] presented Surfpad that corresponds to a new pointing facilitation technique based on a tactile touchpad that supports friction reduction by means of a squeeze film effect. Surfpad preserves the nominal coefficient of friction of the touchpad when the cursor is on a target while reducing the same in all other places. The study compared Surfpad to the Semantic Pointing technique and constant control-display gain with and without distractor targets, and concluded that Surfpad lead to a performance improvement of approximately 9 percent in pointing at small distractor targets. Lévesque et al. [17] validated the effect of programmable friction on the interaction fidelity of a single finger sliding on LATPaD, and discussed its design space. Furthermore, they utilized programmable friction for single finger scrolling interactions [18]. The effect of tactile feedback on several key performance metrics were discussed, and included the identifiability of a set of iconic detents, countability of detents, perception of detent density, and synchronization of tactile feedback. The aforementioned studies are all based on the squeezing air-film effect that produces a smoother surface when compared to the original surface. With respect to electrostatic tactile feedback, the added feedback produces a higher friction level when compared to the original material of a tablet's surface. Therefore, it is unclear as to whether the aforementioned results continue to be effective for electrostatic tactile feedback.

Most previous works on electrostatic tactile feedback focus on the following two aspects: the first include efforts to model the fingertip-surface interface [19], [20], [21], and the second include ways to utilize electrostatic force to enable a variety of tactile feedback designs [4], [22]. Only a few studies examine the effect of electrostatic tactile feedback on users' targeting performance. In 2015, Zhang et al. [23] compared user performance between no feedback and four haptic feedback designs based on either physical or electrostatically feedback. Their results validated that electrostatic tactile feedback improved targeting speed by 7.5 percent when compared to conventional flat touch screens. Although the study added electrostatic tactile feedback to target areas, it did not explore as to whether a continuous electrostatic tactile feedback during the whole sliding process can produce significant differences on the operations performance of pan gestures. Specifically, if the pan movement is assisted by a linear friction force pattern like a virtual spring, i.e., using the electrostatic tactile feedback to provide a damping effect on the rapid sliding movement of the fingertip, it is unclear as to whether the continuous electrostatic tactile feedback assists or degrades the accuracy and speed of pan gestures.

The accuracy and efficiency of gestures under visual feedback were studied by using Fitts' Law [24]. Tran et al. [25] studied accuracy and efficiency of two typical gestures including pinching and spreading gestures. They explored the effect of several parameters including device (mobile phone versus tablet device), sitting postures, gesture size, and border width. The results indicated that the task execution time for different gesture distances and precision levels displayed a surprisingly good fit to a simple Fitts' Law model. Avery et al. [26] analyzed the drawbacks of classic pinch-to-zoom gestures, and concluded that zooming actions followed a predictable ballistic velocity curve and that users tended to pan the point-of-interest towards the center of the screen. The aforementioned studies indicate that quantified correlations between accuracy and efficiency exist for typical gestures with visual feedback. However, extant studies do not explore the manner in which these correlations change when electrostatic tactile feedback is added.

Pan gestures constitute a convenient way to interact with a touch screen, and they typically utilize a single finger to realize target movements. The aim of the present study involves validating as to whether the added tactile feedback improves accuracy and efficiency of pan gestures. That is, different from experimental methods that provided tactile feedback on the ending locations of movements [17], [18], [23] since a linearly increasing friction force is added along the entire sliding trajectory, thereby making it possible to assess the effect of tactile feedback on the moving process.

The study attempts to compare the accuracy and efficiency of pan gestures with respect to two conditions, namely with and without electrostatic tactile feedback. Additionally, it includes exploring the manner in which the completion time of pan gestures evolves with different indices of difficulties. This knowledge can be potentially used to develop novel versatile tactile-enhanced gestures with rich tactile sensation, while simultaneously maintaining acceptable accuracy and efficiency.

3 Electrostatic Tactile Feedback Device and the Overall View of Experiments

3.1 Electrostatic Tactile Feedback Device

A Coulomb force is produced between fingers and the surface while sliding fingers on conductive surface covered

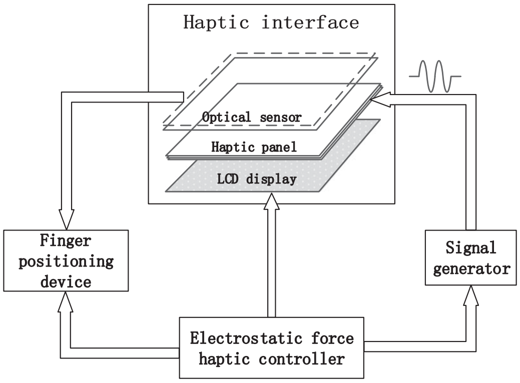

Fig. 1. A functional diagram of a custom-designed electrostatic tactile device.

with a thin insulating layer. Fingers and the surface are considered as two plates of the capacity, and the alternating voltage is loaded to the surface to produce the electrostatic attraction force. Based on this physical principle, an electrostatic tactile display was developed and validated. A functional block diagram is shown in Fig. 1. The haptic interaction component consists of three layers, namely the top optical sensor acquires the touch position of a finger, the middle haptic panel is similar to a traditional capacitive touch screen and generates the electrostatic tactile stimulation, and the bottom LCD screen displays visual information.

A physical prototype of the designed electrostatic tactile display is shown in Fig. 2. The main structure of the proposed display consists of a Microsoft Surface, a Micro-touch screen, a tactile controlling module, and a finger tracking module. The tactile controlling module generates tactile stimuli signals and loads the same to the Micro-touch screen, and thus the related tactile sensation is provided on a fingertip position.

In a manner similar to Tesla Touch [4], [27], the electrostatic tactile display shown in Fig. 2 displays detailed shapes and textures of images presented on the screen. Additionally, different friction patterns are produced by generating different stimuli signals including sinusoidal and square waves [28], [29].

Fig. 2. A physical prototype of the electrostatic tactile display.

3.2 The Overall Design of Experiments

Based on the display shown in Fig. 2, several experiments were conducted in the following three sections. The overall design of the three experiments for a single participant is presented in Fig. 3, which explains the distribution of trials and time interval of each experiment. In Fig. 3, experiment 1 was conduct to analyze the effect of electrostatic tactile feedback on pan gestures (Section 4), experiment 2 was conducted to reveal the relationship between completion time and indices of difficulties (Section 5), and experiment 3 was conducted to evaluate the effect of user performance with tactile feedback (Section 6). The first and the third experiments were conducted in the morning and evening of one day. The total time to complete the second experiment corresponded to approximately 46 minutes, and this experiment was performed in the afternoon of the same day. Given this arrangement, there were at least 3 hours between two adjacent experiments for each participant, and this aided in avoiding fatigue of the finger due to long-time sliding operations.

Twelve participants (five males and seven females) were invited to perform the three experiments, and their averaged age corresponded to twenty-five years. All the participants were familiar with the electrostatic tactile display and used their right hands to operate it. Informed consent was obtained from all participants, and the experimental protocol was approved by the ethical committee of Jilin University. Indoor temperature and humidity were maintained at 23 °C ~ 28 °C and 35 ~ 55 percent, respectively. In order to

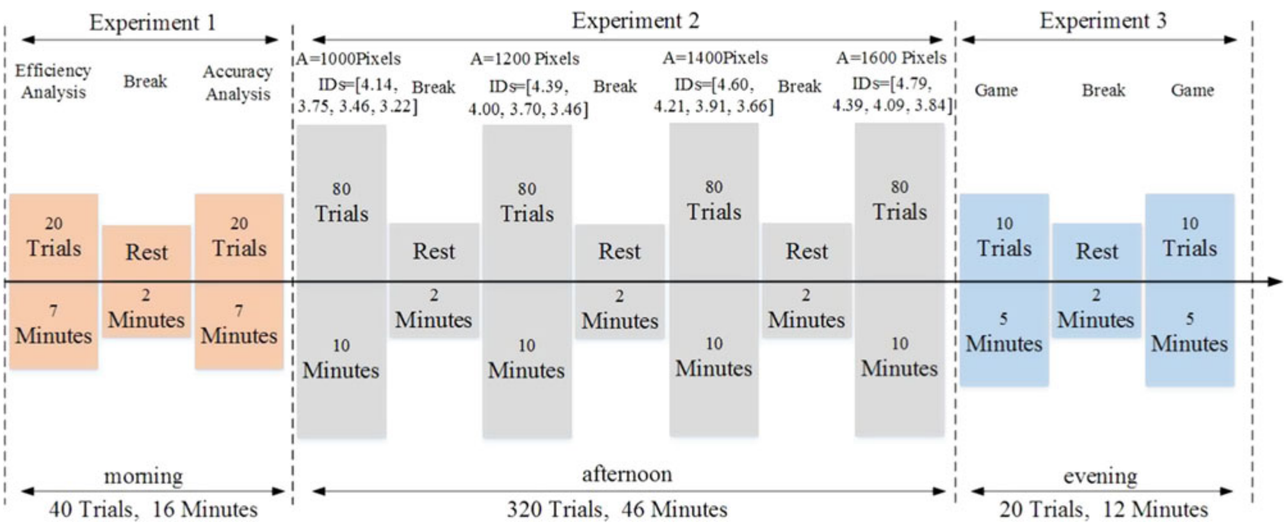

Fig. 3. The overall design of three experiments for a single participant.

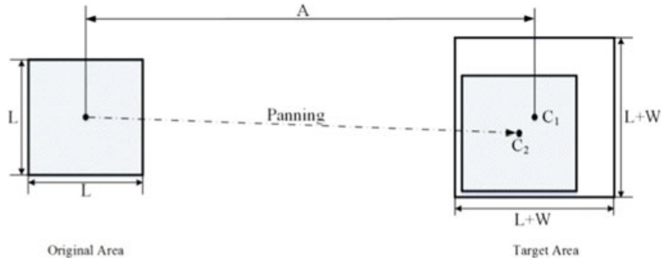

Fig. 4. Measurement of completion time with $\mathrm{A} = 1600$ Pixels and $\mathrm{W} = 30$ Pixels.

reduce the effect of external environments on experiment results, isopropyl alcohol was used to clean screens of the display and fingers of participants.

In Sections 4 and 5, the procedure of a trial is described and includes followings. A participant moves an image from the initial area to the target area using visual feedback. The participant is instructed to lift his/her finger whenever the image is completely inside the target area, and this is denoted as a successful trial. Otherwise, if the participant lifts his/her finger when the image is not fully located inside the target area, then the trial is marked as an error and discarded in the subsequent analysis.

4 Effect of Electrostatic Tactile Feedback on Pan Gestures

In this section, the accuracy and efficiency of pan gestures with electrostatic tactile feedback are evaluated, and compared with those that only rely on visual feedback.

4.1 Efficiency Analysis with Electrostatic Tactile Feedback

1) Experiment Design. The goal of this part involves comparing the efficiency of pan gestures with and without electrostatic tactile feedback. The efficiency is evaluated by the completion time (CT) of moving a picture from an initial position to a target position, while the two positions are defined with a fixed distance A, an allowable error W, size, and the coordinates of centers.

As shown in Fig. 4, A is defined as the distance between the center of the original area and that of the target area. Additionally, W is defined as the maximum allowable error between the center of the target area and that of the final position of the moved image. In the experiment, $\mathrm{A} = 1600$ Pixels and $\mathrm{W} = 30$ Pixels. The length of 9 pixels is equivalent to 1 mm on the surface of the screen, and thus $\mathrm{A} = 177.78$ mm and $\mathrm{W} = 3.33$ mm. Therefore, the side length of the original area and the target area correspond to $L = 268$ Pixels and $L + W = 298$ Pixels, respectively, and the related coordinates of the centers of these two areas correspond to (134 Pixels, 650 Pixels) and (1734 Pixels, 650 Pixels) with respect to the bottom-left corner of the screen.

As shown in Fig. 5, a spring-like linear friction force pattern is produced during the movement process of pan gestures as follows:

$$f = k_1\Delta, \tag{1}$$

where f denotes the expected friction force produced on the user's fingertip, $\Delta \leq A$ denotes the moving distance of an image as shown in Fig. 5, and k_1 denotes a constant denoting the virtual spring like stiffness of the friction force pattern.

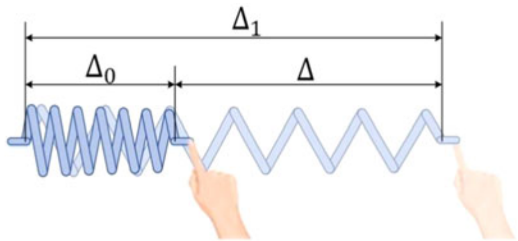

Fig. 5. The relationship between electrostatic force f_e, lateral friction force f and tactile excitation voltage signal V.

In order to produce the expected friction force f, the following force model is utilized

$$f = \mu f_e, \tag{2}$$

where f_e denotes electrostatic force, and μ denotes the friction coefficient.

Based on the principle of electrostatic force control theory, the added tactile excitation voltage signal and the electrostatic force satisfy the following relationship

$$f_e = \frac{\varepsilon S V^2}{2(\frac{T_s}{\varepsilon_s} + \frac{T_p}{\varepsilon_p})(T_s + T_p)} = k_2 V^2, \tag{3}$$

where V denotes the voltage across the finger and the electrodes, ε,ε_s and ε_p denote the permittivity of space, outer skin and insulator, respectively, T_s denotes the skin thickness, T_p denotes the insulator thickness, S denotes the contact area, and k_2 denotes a constant.

Finally, the relationship between the tactile excitation voltage signal and the movement displacement of the fingertip during pan gestures is derived as follows:

$$V = \sqrt{k\Delta}, \tag{4}$$

where k is also a constant and is computed as follows:

$$k = k_1/\mu k_2 = V_P^2/A, \tag{5}$$

where V_P denotes the peak of excitation voltage signal, and A denotes the pre-defined distance for pan gestures.

The goal of the proposed tactile feedback involves simulating a linear friction force pattern similar to a virtual spring with the aim of producing a damping effect on the rapid sliding movement. Given the peak of excitation voltage signal and the selected distance A, the constant k was first obtained by using Eqn. (5). The electrostatic tactile feedback device shown in Fig. 2, aided to measuring the position of the moved image in real-time, and thus the moving displacement Δ was obtained. With Eqn. (4), the excitation voltage signal V was computed. Based on Eqn. (2) and (3), the friction force f was proportional to the square of excitation voltage signal V. Therefore, an increase in the moving displacement Δ during the sliding movement led to an increase in the excitation voltage signal V, and this yielded a continuously increasing friction force f.

2) Experiment Procedure. Prior to the formal experiment, a pilot experiment was performed to ensure all participants were familiar with the experimental equipment and the

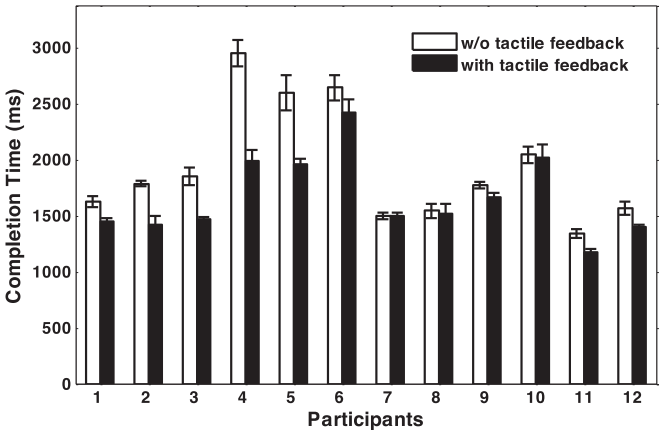

Fig. 6. The completion time with and w/o electrostatic tactile feedback ($\mathrm{A} = 1600$ Pixels, $\mathrm{W} = 30$ Pixels).

sliding movement task. Each participant performed 30 trials under each of the two conditions: with or without electrostatic tactile feedback. The arrangement of such a pilot experiment ensured that participants finished all trials in a stable performance in the formal experiment.

In the formal experiments, each participant participated in two groups of experiments. In group 1: only visual information was provided, and in group 2: both tactile information and visual information were provided. Half of the participants first participated in the experiments termed as group 1, and subsequently participated in the other group of experiments, conversely, the other half of the participants participated in two groups of experiments in the opposite order to avoid "the practicing effect". In both groups, each participant moved the image from the initial area to the target area and repeated the same ten times. Each participant had two minutes between repetitive experiments to rest, and the time taken by the participants to complete the experiments approximately corresponded to sixteen minutes.

The completion time of pan gestures was computed as

$$CT = t_2 - t_1, \tag{6}$$

where t_1 and t_2 denote the moments when a participant's finger touches and lifts the image, respectively.

3) Experiment Results. In the following analysis, the failure rates for the recorded completion time with and without tactile feedback are 0.833 and 1.667 percent, respectively. With respect to the recorded data, the histogram of the average and the standard deviation of completion time for each participant are shown in Fig. 6. Evidently, all participants under electrostatic tactile feedback spent a shorter time to move the image to the target area, and this is especially applicable for the fourth and fifth participants. For a total of twelve participants, the averages of the completion time with and without electrostatic tactile feedback correspond to 1688.4 ms and 1863.5 ms, respectively, and the related standard deviations correspond to 11.72 and 12.95. With the SPSS software, the significance analysis results of ANOVA correspond to $F(1,11) = 11.230,\ p < 0.05$ and $F(1,11) = 1.880, p > 0.05$.

The results illustrate that when the mean of completion time is considered, the pan gestures with electrostatic tactile feedback provide higher efficiency.

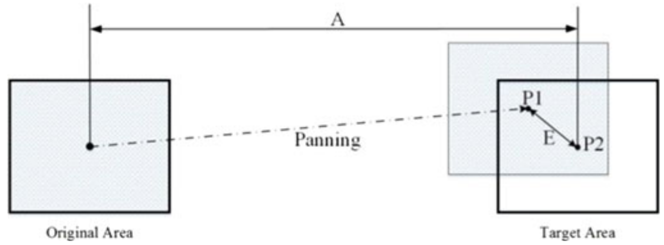

Fig. 7. Measurement of the position error with $\mathrm{A} = 1600$ Pixels and $\mathrm{CT} = 1800$ ms.

4.2 Accuracy Analysis with Electrostatic Tactile Feedback

1) Experiment Design and Procedure. The goal of this part involves comparing the accuracy of pan gestures with and without electrostatic tactile feedback. The position error E with the selected distance A and completion time CT is measured. As shown in Fig. 7, the distance A corresponds to 1600 Pixels. The allowable CT is based on the average of Section 4.1 and is set at 1800 ms. Additionally, both the lengths of the original and target areas correspond to 268 Pixels, and the related position coordinates of centers are the same as shown in Fig. 4. The position error E is defined as the one between the center of the target area and that of the final position of the moved image. As shown in Fig. 7, E is computed as

$$E = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}, \tag{7}$$

where (x_1, y_1) and (x_2, y_2) denote the coordinates of P1 and P2, respectively.

The experimental process was similar to that of Section 4.1 and the same participants were invited to perform this experiment. In two conditions with and without electrostatic tactile feedback, each participant conducted ten trials with $\mathrm{A} = 1600$ Pixels and $\mathrm{CT} = 1800$ ms.

2) Experiment Results. With respect to the recorded data, the histogram of the average and the standard deviation of position errors for each participant are shown in Fig. 8. It is seen that the fifth participant provides almost the same position errors in two conditions, while the position errors with electrostatic tactile feedback for the other eleven participants are smaller than those that only rely on visual feedback.

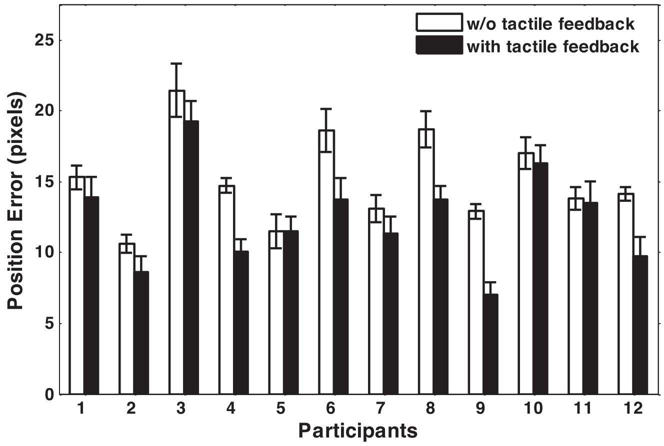

Fig. 8. The position error with and w/o electrostatic tactile feedback ($\mathrm{A} = 1600$ Pixels, $\mathrm{CT} = 1800$ ms).

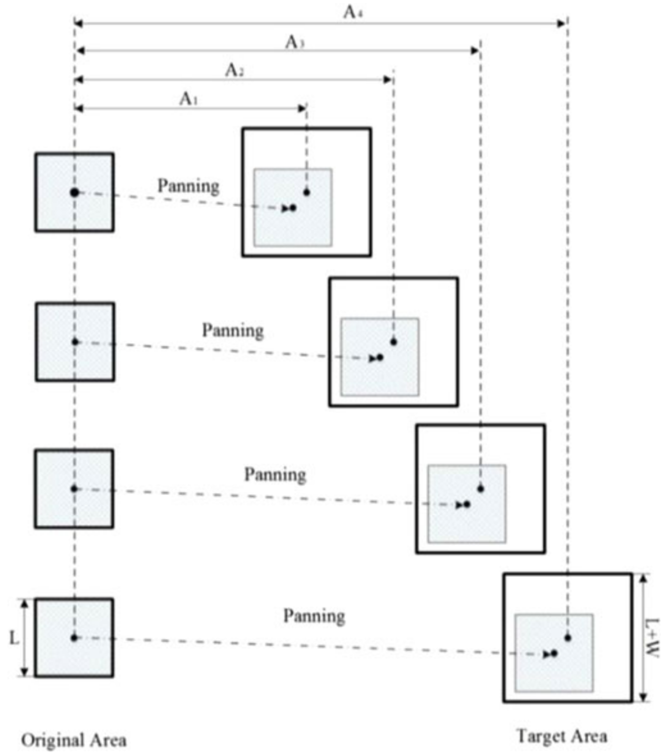

Fig. 9. Measurement of the completion time with different values of A (1000, 1200, 1400, and 1600 Pixels).

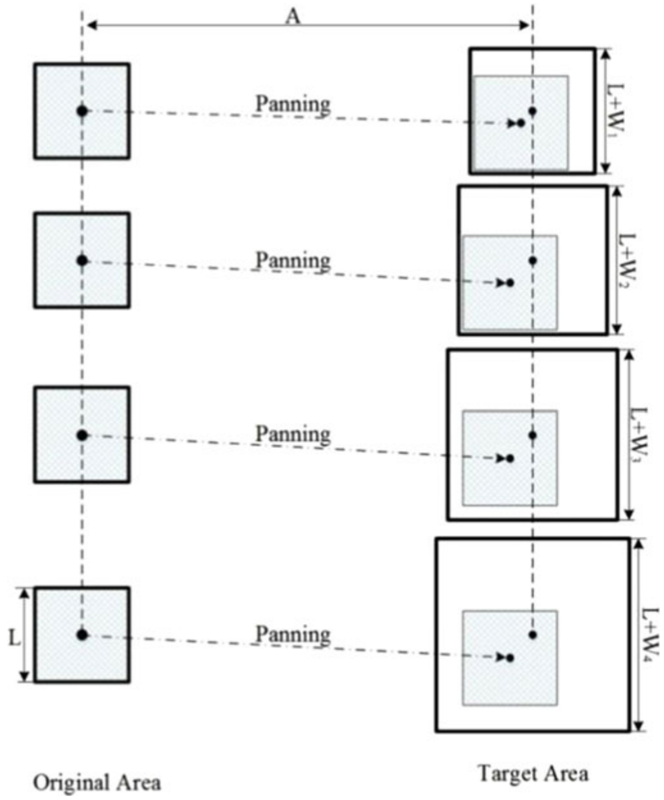

Fig. 10. Measurement of the completion time with different values of W(60, 80, 100, and 120 Pixels).

For a total of twelve participants, the averages of the position errors with and without electrostatic tactile feedback correspond to 11.5 Pixels and 14.5 Pixels, respectively, and the related standard deviations correspond to 1.34 and 1.57. With the SPSS software, the significance analysis results of ANOVA correspond to $F(1,11) = 19.601$, $p < 0.05$ and $F(1,11) = 13.020, p < 0.05$.

The results indicate that pan gestures with electrostatic tactile feedback are more efficient than those that only rely on visual feedback.

4.3 Discussions

From above two experiments, it is concluded that accuracy and efficiency of pan gestures with the added electrostatic tactile feedback are significantly better than those of the pan gestures without tactile feedback. The main reasons for this phenomenon are explained as follows:

The friction force is typically very small for a smooth screen surface composed of glass material. While panning a picture with a high sliding speed on this type of a screen surface, the inertia effect causes the picture to be moved to a further area as opposed to the target area [30]. With respect to the experiment in Section 4.1, an extra adjustment process is typically required to reduce the position error to the allowable W, and this makes the related completion time longer. With respect to the experiment in Section 4.2, the completion time is fixed, and thus the extra adjustment process is not allowed to occur, thereby leading to an increased position error.

When electrostatic tactile feedback is added, the friction between the participant's finger and the screen surface is increased [4], [15]. With the added friction, the inertia effect of a highly sliding speed motion is reduced to a certain extent. Additionally, the added friction is produced by the electrostatic force, and thus its value is typically small. This implies that the sliding speed of pan gestures is slightly affected. With respect to the two experiments in Sections 4.1 and 4.2, the trade-off between the inertia effect and the moving speed is reached given the added electrostatic tactile feedback. Therefore, it is easier to move the picture to the target area, and the extra adjustment process that affects completion time or position errors is efficiently avoided.

As indicated in the first experiment, the completion time of pan gestures is determined by the moving distance A and the allowable error W. However, it is unclear as to the manner in which these two factors influence completion time, and as to whether a determined relationship exists between completion time and these two variables. Therefore, further studies should be conducted to reveal the correlation between completion time and index of difficulties.

5 The Relationship between Completion Time and Index of Difficulties

5.1 Experiment Design and Procedure

This experiment is used to explore the relationship between the completion time of pan gestures with electrostatic tactile feedback and the two other independent variables. As shown in Figs. 9 and 10, two independent variables include: 1) the distance A between the center of the original image position and that of the target area that is selected as corresponding to 1000 Pixels, 1200 Pixels, 1400 Pixels and 1600 Pixels; 2) the maximum allowable error W between the center of the target area and that of the final position of the moved image that is selected as corresponding to 60 Pixels, 80 Pixels, 100 Pixels and 120 Pixels.

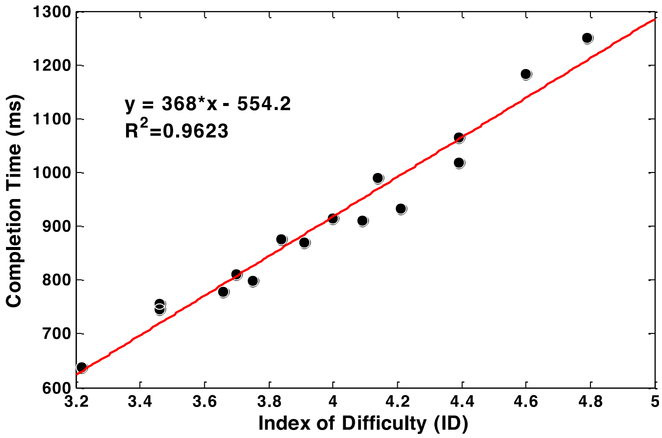

Fig. 11. The relationship between CT and ID using the Fitts' model.

Given the values of A and W, 16 different combinations were designed to measure completion time. For each combination, all participants were required to perform twenty repetitions of pan operations with electrostatic tactile feedback, and the related completion time was recorded in the same manner as in Section 4.1.

5.2 Experiment Results and Discussions

In order to determine the relationship between completion time (CT) and the other two independent variables A and W, Fitts' Law is utilized to analyze the recorded data. Typically, Fitts' Law is defined as follows

$$CT = a + b \cdot \log_2\left(\frac{A}{W} + 1\right), \tag{8}$$

where a and b denote constants, and $\log_2(\frac{A}{W} + 1)$ is defined as the index of difficulties (ID).

In this study, the influence of ID on CT is systematically analyzed by utilizing Fitts law. The related result of the experiment is shown in Fig. 11. It should be noted that the failure rate for the results is 1.875 percent.

From Fig. 11, the completion time becomes longer as the index of difficulty increases. When Fitts' model is used, the two constants a and b are -552.4 and 368, and the correlation coefficient is 0.96. This result implies that the relationship between CT and ID of pan gestures with electrostatic tactile feedback can be well described by the Fitts' model.

6 A "Tactile Fruit Sorting" Game

6.1 Experiment Design

Based on Section 5, it is concluded that the completion time of pan gestures with electrostatic tactile feedback followed Fitts' law. Given these results, a novel "Tactile Fruit Sorting" game was designed. The goal of the game involved validating as to whether the added tactile feedback enhances users' experience when performing multiple and quick pan gestures.

The graphic scene of the "Tactile Fruit Sorting" game is shown in Fig. 12. During the game, five types of fruits including watermelons, apples, pearls, tomatoes and cherries appear in random positions in the top area of the screen, and subsequently move in a randomized direction corresponding to down, left or right with a constant speed. Users are required to drag the randomly appearing fruit to one of the target fruit images that possess the same shape as the selected fruit. For example, when a player's finger touches a fruit, the fruit follows the finger's trajectory. Another fruit disappears when the player lifts his/her finger, and subsequently appears in a random position from the top of the screen. It then moves in the same aforementioned manner.

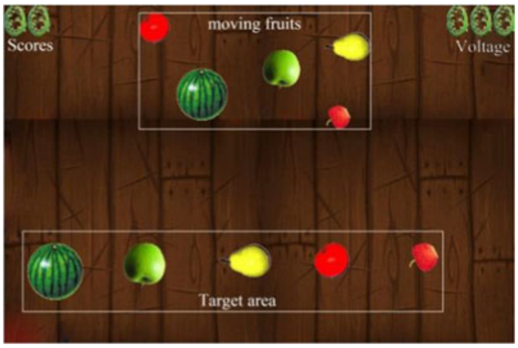

Fig. 12. The graphic scene of "Tactile Fruit Sorting" game.

The five static fruit images at the bottom of the screen correspond to the target areas for pan movements. The length and width of these target areas exceed the size of those dragged fruit by 30 Pixels, i.e., W = 60 Pixels. When a player's finger presses the fruit, the system records the center position (p1) of the fruit and the center position (p2) of the corresponding target image. This is followed by obtaining the distance (A) between two positions. Based on the results in Section 5, the allowable completion time CT for moving the fruit to the target region is obtained by using Eqn. (8).

The time taken to complete a session of this game corresponds to 30 s. Three levels of difficulty are defined in each session. For the first 10 s, the allowed time for the fruit to be dragged corresponds to (CT + 500) ms, and this implies that the difficulty level is low. In the following 10 s, the allowed time corresponds to (CT) ms, and this indicates that the related difficulty level is medium. For the last 10 s, the allowed time for the fruit to be dragged corresponds to (CT-500) ms, and this indicates that the related difficulty level is high.

As shown in Fig. 12, the "00" at the upper left corner of the graphic represents the players' scores, and the "000" at upper right corner of the interface represents the added voltage. The value of scores is based on the difficulty level of each trial. For trials within the first 10 s, watermelons, apples, pears, tomatoes and cherries are all defined corresponding to a score of 1. With respect to the other two levels of difficulty, an extra 1 and 2 scores is obtained for each type of fruit.

In the game, each pan movement is defined as a trial from the selection of a fruit image until the release of the fruit image. In each session (30 s), the number of successful sorting trials and the success rate are adopted as quantified metrics to evaluate users' performance. The success rate is defined as the ratio between the number of successful sorting trials and the number of all sorting trials in a session.

The actual process for users to drag the watermelon to the target area is shown in Fig. 13. Additionally, the real-time interaction process is also illustrated in the supplementary

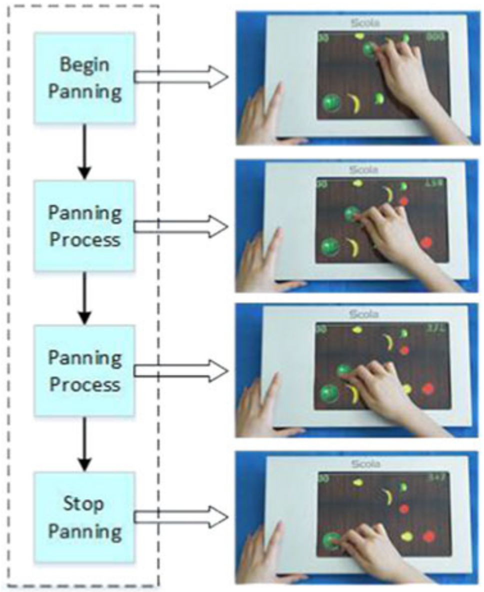

Fig. 13. The actual process involving the dragging of a watermelon to the target area.

video, which can be found on the IEEE Xplore Digital Library at http://ieeexplore.ieee.org/document/8013837/.

6.2 Experiment Procedure

In order to evaluate the efficiency of this game, the twelve participants were invited to play the game under the following two conditions: with and without electrostatic tactile feedback. Each participant conducted ten sessions for each condition. All participants were randomly divided into two groups with an equal number of participants in each group. The first group first played ten sessions under the condition without tactile feedback, and then played ten sessions with tactile feedback. The second group played this game under two conditions in a reversed order.

After completing the game, the players were asked to complete a questionnaire form to evaluate user experience of interest. The form included the question "how high do you rate the interest of games with and without the electrostatic tactile feedback respectively". A Likert scale was used to evaluate the extent of interest. Specifically, the extent of

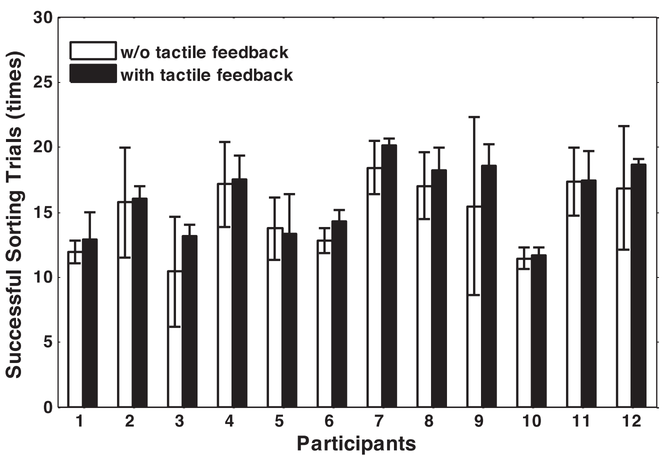

Fig. 14. Successful sorting trails with and w/o electrostatic tactile feedback.

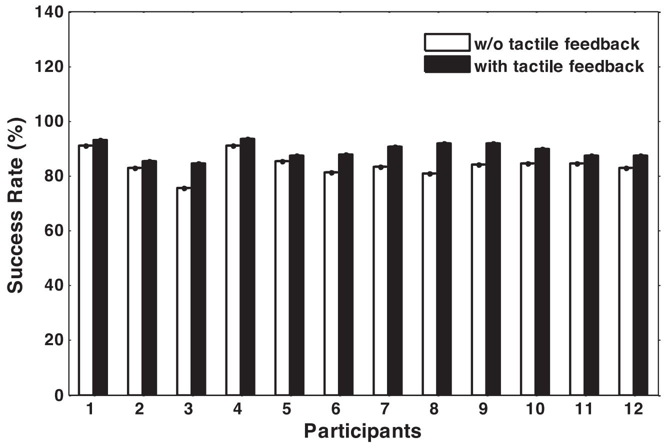

Fig. 15. Success rate with and w/o electrostatic tactile feedback.

interest was divided into five levels, and a score of 1 indicated the lowest level of interest, and a score of 5 indicated the highest level of interest.

6.3 Experiment Results and Discussions

The average and standard deviation of each participant's performance under the two conditions are shown in Figs. 14 and 15 that illustrate the successful sorting trials and the success rate in each session, respectively. With respect to all participants, the average number of successful sorting trials with and without electrostatic tactile feedback corresponds to 15.93 and 14.25 times, respectively, in a session, and the related standard deviations correspond to 2.42 and 2.56. With the SPSS software, an analysis of ANOVA indicates the significance difference of the average of the successful trials between the two conditions with $F(1,11) = 12.092$, $p < 0.05$. Additionally, the average success rates of dragging fruits to target areas in a session with and without electrostatic tactile feedback correspond to 89.44 and 83.15 percent, respectively. The results indicate that the added tactile feedback leads to an improvement in the users' performance.

The subjective evaluation result is shown in Fig. 16. It is observed that all participants with the exception of the tenth participant consider the novel game with electrostatic tactile feedback as more interesting, and the related significance analysis result of ANOVA corresponds to $F(1,11) = 41.12$, $p < 0.05$. Furthermore, from the results of the questionnaire

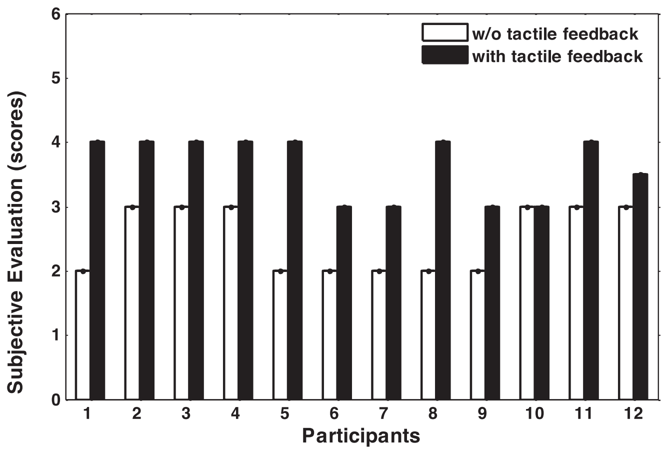

Fig. 16. Subjective evaluation with and w/o electrostatic tactile feedback.

after the experiment, none of the participants reported any fatigue issues with the added electrostatic tactile feedback.

Therefore, both subjective and objective evaluations indicate that the added tactile feedback improves players' performance and enhances users' interest in the game. A potential reason for this phenomenon is that linear friction force alleviates the inertia effect of a sliding finger, and thereby achieves an accurate and quick localization on the touch screen. The continuous electrostatic tactile feedback helps in maintaining a trade-off between the moving speed and the accuracy, and thus it is easier for participants to rapidly drag the fruits to corresponding target areas.

A video revealing the procedure of this game is provided to further illustrate the above experiment results. As observed in this video, the trials successfully sorting fruits with and without tactile feedback are 16 and 13 times, respectively, and the corresponding success rates in the two conditions are 88.89 and 81.25 percent.

7 Conclusion

In this study, a custom-designed electrostatic tactile display was used to initially compare the accuracy and efficiency of pan gestures under two conditions: namely with and without electrostatic tactile feedback. This was followed by exploring the manner in which the efficiency evolved with different indices of difficulties (ID).

The experimental results with twelve participants illustrate that the accuracy and completion time (CT) of pan gestures with electrostatic tactile feedback significantly exceed those without tactile feedback. Furthermore, the relationship between CT and index of difficulty (ID) satisfies Fitts' Law with the correlation coefficient exceeding 0.9. Based on the findings, a "Tactile Fruit Sorting" game was designed, and subjective and objective evaluations were performed. The results indicate that added tactile feedback enhances both user performance and interest in the game. This knowledge can help in creating novel interaction paradigms for touch screens, such as tactile-enhanced gestures, by fully utilizing added tactile feedback.

The experimental results indicated that linear friction force alleviates the inertia effect of a sliding finger. Thus, a natural idea involves exploring the effect of other friction patterns to achieve an accurate and quick localization on a touch screen. For example, it is not clear as to whether nonlinear friction force patterns perform better performance than the current linear friction force. A future study involves examining the effect of nonlinear friction force patterns on pan gestures. Furthermore, interesting topics include investigating the effect of electrostatic tactile feedback on other typical gestures such as pinch and spread by using two fingers.

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