An Empirical Characterization of Touch-Gesture Input-Force on Mobile Devices

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ABSTRACT
Designers of force-sensitive user interfaces lack a ground-truth characterization of input force while performing common touch gestures (zooming, panning, tapping, and rotating). This paper provides such a characterization firstly by deriving baseline force profiles in a tightly-controlled user study; then by examining how these profiles vary in different conditions such as form factor (mobile phone and tablet), interaction position (walking and sitting) and urgency (timed tasks and untimed tasks). We conducted two user studies with 14 and 24 participants respectively and report: (1) force profile graphs that depict the force variations of common touch gestures, (2) the effect of the different conditions on force exerted and gesture completion time, (3) the most common forces that users apply, and the time taken to complete the gestures. This characterization is intended to aid the design of interactive devices that integrate force-input with common touch gestures in different conditions.

Author Keywords
Force sensing; characterization; touch screen gestures; mobile devices; force profiles.

ACM Classification Keywords
H.5.2. User Interfaces: Evaluation / Methodology.

General Terms
Human Factors; Design; Experimentation.

INTRODUCTION

Force plays an important role in our interactions with the surrounding environment, e.g. from carefully holding a newborn child, to vigorously opening the lid of an uncooperative food container. Force is also prevalent in artistic expression: pianists use force to amplify specific notes, and artists vary brush-stroke force to emphasize features in a painting. This routine application of varying force in everyday life has implications for the design of interactive systems. Interactive force sensitive devices already exist in gaming (e.g. PlayStation 3 controller), design (Wacom tablets), and music (e.g. electronic keyboards). Numerous research prototypes employ force sensors to augment existing devices such as mobile phones (e.g. [1, 11, 28]), keyboards and mice (e.g. [3, 5]), and develop novel techniques (e.g. Zliding [18]). For example, force input can be used to replace larger hand motions (e.g. flicking [11] on a touch screen device) with more subtle motions [25] such as pressing harder or softer on a button.

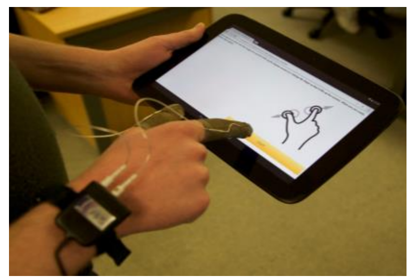

Figure 1: A study participant wearing the FingerTPS equipment performing a zooming-in task on a Nexus 10 tablet.

Despite the wide presence of numerous commercial and research-based force sensitive devices, we still lack a thorough understanding of the behavioral and quantifiable characteristics of force that users exert when carrying out common touch gestures (e.g. zooming into an image using a pinch gesture). This paper provides such a characterization for interactive mobile surfaces by: (1) presenting force profile graphs that illustrate high-level behaviours of touch gestures, (2) describing the effect of different conditions on force and time, and (3) providing the most common forces applied, and the time taken to complete the gestures.

This characterization benefits designers of interactive devices to integrate force as an input modality with standard touch gestures such as zooming, rotating, panning, tapping, and typing (as discussed in [13, 21]). Furthermore, our characterization informs the design of such systems in different conditions (or contexts of use). We believe that the prevalent use of touch gestures and the additional interaction dimension provided by force-input (e.g. [15]) can lead to novel and useful interaction techniques.

To develop this characterization, we conducted two lab-based user studies with 14 (8 male, 6 female) and 24 participants (12 male, 12 female) respectively. In both

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studies, participants wore the FingerTPS force sensing finger gloves[1] (Figure 1) and completed a series of touch gestures (pinching, panning, tapping, typing, and rotating) on standard touch screen devices. The force sensors were included in the wearable equipment rather than integrating sensors into the devices in order to enable the findings to be generalizable across similar devices. The first study involved a single condition (i.e. seated, tablet and without time-pressure) with multiple repetitions of each gesture in order to derive baseline interaction force profiles. In the second study, participants completed the gestures under varying conditions (seated, walking, phone, tablet, urgent, non-urgent) in order to examine how these conditions affected the baseline force profiles.

RELATED WORK

Force input has been widely researched in the context of input/interaction techniques, ways of sensing force, and its application on interactive mobile surfaces. Force input, for instance, removes restrictions on screen real-estate by providing fine-grained control for interactions such as menu traversal [28]. Heo and Lee [9] suggest that using force is more natural compared to traditional touch screen interactions (e.g. multi-touch to flick a page of an e-book). Hwang et al. [11] state that force input can free users from repetitive movements (e.g. flicking) as well as free up the non-dominant hand [10, 26].

Force Input with Mobile Devices

Common force input tasks on mobile devices include menu-selection [27, 28], and text-entry [1, 4, 15]. Wilson et al. [28] experimented with menu-selection techniques such as *Dwell* (selecting an item by remaining at the target) and *Quick Release* [19]. Brewster and Hughes [1] designed a mobile keyboard which mapped soft and hard presses to lower and uppercase letters (removing the need for a shift-key). McCallum et al. [15] augmented the standard 12-button mobile keyboard to include force sensing up to four levels (soft press invokes first character, harder press second character, etc.). An evaluation of the prototype suggested that users would require more training (due to errors). In addition to text-entry, Clarkson et al. [4] also explored mapping force levels to scrolling and the navigation of 3D objects. Stewart et al. [25] investigate force interaction using one and two-sided mobile devices. The authors explore an iPhone Sandwich device [6] and found that force interaction in a mobile setting is preferable using the two-sided interaction paradigm (i.e. grasping the device with force sensors on the front and back).

Scott et al. [24] suggested more complex force interactions such as stretching, squeezing, bending, and twisting. With full screen deformations, such as those in the Gummi concept [23], not yet technologically possible, they explored minor deformations suitable for current LCD-displays. Their user study showed promising results for the twist and bend interactions with improved proficiency in task completion (e.g. map navigation, text entry) over time.

Holman and Hollatz [10] and Wilson et al. [26] experiment with using the edges of mobile devices to apply force input. Wilson et al. [26] carried out a comparative user study with normal touch screen gestures, and found that workload ratings remained the same, whilst force input was slightly faster for carrying out tasks such as zooming and rotation. Similarly, Holman and Hollatz's Unifone [10] prototype showed better performance when comparing force-based input with touch-input for tasks such as map navigation.

Combining Force with Touch Gestures

The use of standard touch gestures is becoming prevalent in Smartphones and tablet devices and therefore provides a useful opportunity for combining force with such gestures. Rendl et al. [20] conducted a study and found that users were able to effectively carry out multi-touch gestures (pinch, swipe and stretch) with a small number of force levels. Heo and Lee [9] explored the usability of force sensitive tapping, pivoting, pressing, sliding and dragging (derived from a general tap and a slide) and found higher degrees of force levels can be problematic for users. Lee et al. [14] found that touch gestures that involve up and down movements are preferred with force input. Harrison and Hudson [8] describe the applications of *shear* gesture interaction (force and directionality sensing), e.g. applying a clockwise motion with a finger to increase media volume.

Approaches for Measuring Force Input

To measure force input, both software and hardware based approaches have been utilized. One common example involves Force Sensing Resistors (FSRs), which consists of flat polymer-based sheets fitted with semi-conductors and electrodes [29]. Several research prototypes [6, 9, 24, 26, 28] have produced accurate force readings, while the challenges were concerned with integrating the external FSRs into existing devices (i.e. selecting appropriate locations), achieving optimal sensitivity (e.g. the iPhone Sandwich [6]) for accurate force readings, and handling interference from device deformations [24].

Other approaches have utilized existing mobile device technology. VibPress [11] uses mobile phone hardware such as the accelerometer and the built-in vibration motor to measure force, which resulted in relatively high accuracy during a user study. Goel et al. [10] use a mobile phone's gyroscope and vibration motor to detect light, medium and heavy force input. Hwang and Wohn [12] utilize the built-in microphone of a mobile device and map sound amplitude to force-input levels. A user study showed high accuracy at lower levels (95%), and slightly lower accuracy at higher levels (71.3%). A similar approach is used by Pedersen and Hornbaek [16] involving a method that detects the amplitude in the sound waves generated by a finger tap.

[1] http://www.forceprofile.com/products-fingertps (last accessed 13th of June 2014).

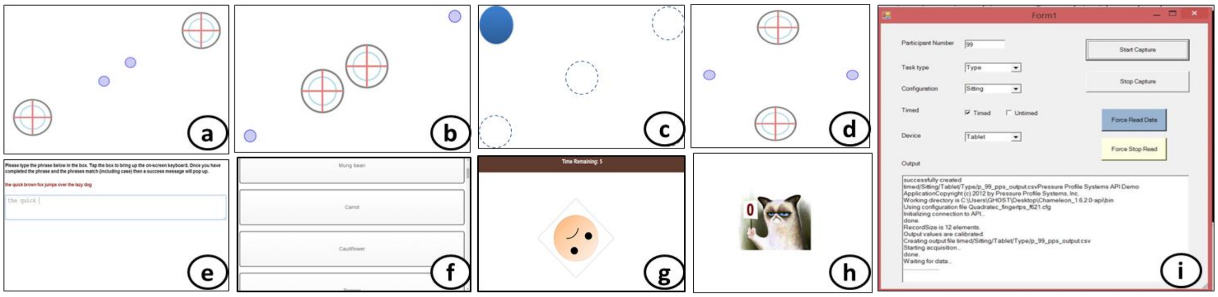

Figure 2: Touch gesture application - (a) zoom-out task, (b) zoom-in task, (c) tapping task (dotted circles show where next circles appear), (d) rotate task, (e) typing task, (f) panning task, (g) study 2 rotate task, (h) study 2 zooming task, (i) capture application

The authors note the importance of device surface acoustics (the material and how it amplifies sound), coupled with microphone positioning to achieve optimal force detection. Another interesting technique is proposed by Boring et al. [2], which uses contact size of a thumb (i.e. *Fat Thumb*) rather than force sensors to measure force. This approach also enables users to change contact size without actually applying more force, and thus avoiding friction (e.g. the interactions proposed by Roudaut et al. [22]).

INVESTIGATING FORCE PROFILES

To characterize force input patterns when carrying out touch gestures on mobile devices, we conducted a controlled laboratory user study. The study provided baseline force profiles that were used in study 2 to examine the impact of different conditions.

Selecting Gestures

There are four common, low-level touch gestures that form the basis for the majority of interaction: tapping, panning, zooming, and rotating. We used the de-facto standard actions for these gestures (single finger tap, single finger pan, pinch-to-zoom, two-finger rotate) in the user studies by asking participants to perform a number of tasks (described in the next sections).

Experimental Setup

We used the following hardware and software to prompt user tasks and record input forces: A web-based application (JQuery/PHP) was developed to include tasks based on the gesture interactions described above. A Samsung Nexus 10 inch tablet was used to display the web-application. Study participants wore the FingerTPS force sensing system, which included wearables on fingers equipped with force sensors, and a Bluetooth module that wirelessly captured sensor data (see Figure 1). Finally, a C# application controlled data capture and saved sensor data including timestamps in milliseconds and force values in grams, as CSV files (Figure 2i), which can be found online[2].

Web-Based Touch Gesture Application

The following tasks were supported by the web application:

Zooming: Users must pinch two circles on the screen, which served as start locations for the index finger and thumb, to target locations shown as traditional crosshair targets. This was split into two tasks, i.e. zooming in (Figure 2a) and zooming out (Figure 2b).

Tapping: Users tapped on blue circles that appeared on the screen every 3 seconds with their index finger as target selection (see Figure 2c). The circles appeared on the four corners and the center of the display. Once a circle was pressed, it disappeared to confirm selection and to prompt the next circle.

Rotating: Users were asked to rotate two circles 90 degrees anti-clockwise using their thumb and index finger towards target locations shown as two crosshair targets (Figure 2d).

Typing: Users typed a phrase ("The quick brown fox jumps over the lazy dog") using their index finger, and without auto-complete or other methods such as Swipe (Figure 2e). The task is completed once users have correctly typed the given phrase. While typing is simply a series of tapping actions, users are typically well practiced in rapid entry.

Panning: Users must carry out the panning action on a list (Figure 2f) to simulate a "browsing" action (i.e. scroll down a list using their index finger).

FingerTPS Configuration

The FingerTPS system consists of a set of force sensitive finger gloves that wirelessly send real-time sensor readings via Bluetooth to a USB receiver. Once the sensors are calibrated, the force data was recorded in units such as grams. The C# control application (Figure 2i) enabled us to avoid capturing unusable data when participants were idle. Given the nature of the gestures used in the study, only two finger sensors were required (thumb and index finger). The sensors were capacitive, which enabled participants to normally carry out touch screen interactions.

Method

Participants were required to carry out each of the touch gesture tasks on the tablet. All tasks, except the typing task (which involved typing out a phrase, i.e. 43 repetitions), involved 5 repetitions each.

[2] http://www.scc.lancs.ac.uk/interactivesystems/projects-/TouchForceCharacterisation/

Participants

Fourteen participants (6 female, 8 male) with an average age of 30.43 years took part in the study. Each participant took approximately 20 minutes to carry out the study and was provided with refreshments. Individual tasks took between 2 to 5 minutes to complete. All 14 participants were highly experienced with touchscreen devices and 5/14 participants indicated that the force sensing equipment may have changed the way in which they would normally carry out the touch gestures. Two participants were left-handed and they carried out the rotation task clockwise. Further, the force-sensing finger gloves could be worn on either hand.

Procedure

Participants were asked to wear the force sensing equipment, which was then calibrated in order to address individual differences in finger size and in the exertion of the baseline calibration force (i.e. 464 grams). Following this, they were provided instructions for carrying out the gestures, which began with a trial interaction to ensure they understood the task. Once the tasks were completed, a short demographic questionnaire was provided.

Results

Data Analysis

We employed a systematic process, which is described next, that enabled us to generate profile curves of input gestures (e.g. pinching, tapping, etc.).

Preprocessing and Thresholding: As the sensor noise (when participants were not applying force) contained minor peaks above 0 grams, we applied a threshold above the sensor baseline. This was set each time the sensor was calibrated and removed noise from the analysis, whilst also making it easier to extract the peaks. For each participant, the threshold was examined visually to ensure valid data was transferred into the analysis. This also accounted for calibration drift across interaction repetitions.

Normalization and Interpolation: The time taken to complete a task was different for each participant and therefore the time values of all gestures were normalized with a scale of 1. We then derived 100 sample points from the gesture repetitions by using linear interpolation with the known force values. Interpolation was used in order to derive equal numbers of sample points such that the gesture repetitions could be directly compared and clustered.

Clustering and Averaging: The k-means clustering algorithm was used to classify similar repetition curves which enabled us to, for instance, differentiate between users who may initially press harder compared to others. To achieve this, the data was organized such that all repetitions were time-normalized and applied into an $N \times M$ matrix where N is the repetition and M is 100 interpolated time index values. This enabled direct comparison between the individual repetitions for clustering. We then searched for the lowest value of K that classified all the observed data; starting with a high value of K (K=N) and iteratively reducing it until all visually similar shapes were placed in the same cluster. Clusters that represented less than 10% of the repetitions were disregarded as outliers. To ensure the resulting clusters made sense in context, the results were inspected visually to ensure that the clusters accurately represented different observed force-profile graph shape-characteristics described later. After the gesture repetitions were partitioned, the force values were averaged and force-normalized to produce representative profiles for the gestures. These are discussed in the next sections.

Force Profiles

The force profiles are presented as force and time-normalized curves to depict the shape profile of force for each input gesture. Therefore, the actual force and time values were omitted as we were interested in the shape of the curves, which provide high-level descriptions of how users apply force over time. In cases where more than one curve is described we calculated the difference of all points between the normalized curves and report this as a percentage for comparison purposes. In addition, repetitions with incorrect sensor readings were removed from the analysis. The expected number of total repetitions for each gesture was 602 for typing, and 70 repetitions each for tapping, panning, rotating and zooming. The repetitions below the expected number were caused by unusable sensor data where participants did not press down on the force sensor attached to the finger gloves. The repetitions above the expected number were caused by the occasional unresponsiveness of the gesture application, leading participants to press twice.

Typing: The force profile for typing (Figure 3) shows a short press as illustrated by the sharp increase in curve slope, followed by a short decrease in curve slope until the peak is reached. This is followed by the sensor drop-off. Typing typically consists of short interactions similar to how we type with physical keyboards (common touch screen keyboards also yield different characters with a long press, however this was not required in our study). In total, 422 repetitions (i.e. key presses) were analyzed.

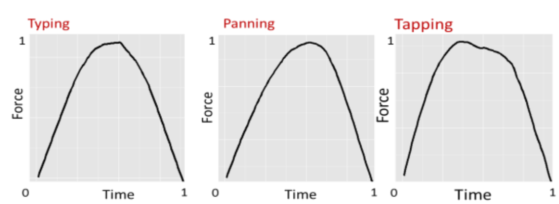

Figure 3: Force profiles for (left) the typing touch gesture, (middle) the panning gesture, (right) the tapping gesture.

Panning: The panning profile curve (Figure 3) illustrates an initial sharp increase followed by a decrease in curve slope, until peak force is reached. The short press indicates a “flicking” action to browse through a list. In total, 67 repetitions were analyzed.

Tapping: The tapping profile (Figure 3) has a larger plateau around the peak indicating a longer press (e.g.

compared to typing and panning). The plateau after the peak is reached indicates that the press is held down longer compared to the previous two gestures. A tap interaction is typically ensued by expecting feedback that the button has been pressed, thus causing a plateau in the peak region of the interaction. The tapping task analysis consisted of 78 repetitions in total.

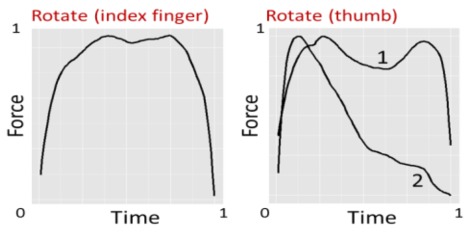

Figure 4: Force profiles for (left) the index finger during the rotate gesture, and (right) the thumb.

Rotating: The force values for the index finger and thumb were analyzed for the rotating touch gesture (Figure 4), revealing a single profile graph for the index finger and two distinct profiles for the thumb. The index finger curve shows a rapid increase to the peak force, followed by force variations (caused by the continuity of a rotate interaction) and the sensor drop off. The thumb analysis revealed two profile curves: curve 1, which resembles the shape of the index finger profile albeit with a larger decline in force applied mid-interaction. In contrast curve 2 shows a gradual decrease in force immediately after peak force is reached (i.e. participants initially pressed hard on the screen, followed by gradually reducing force). The difference between curves 1 and 2 is 35.82%. It was evident that the index finger had more consistent coordination (in terms of force) in comparison to the thumb. The analysis involved 68 index finger repetitions and 43 thumb repetitions.

Zooming: The zoom-out gesture (Figure 5a and 5b) consists of a single profile curve for the index finger (70 repetitions) and two profile curves for the thumb (65 total repetitions). The index finger curve shows an initial hard press and then easing-off towards the end of the gesture. Curve 2 for the thumb is consistent in shape with the index finger. However, curve 1 shows more variation in force once peak force is reached, indicating a harder press throughout the interaction. The difference between the two thumb profile curves is 12.43%.

The index finger and thumb during the zoom-in gesture (Figure 5) indicate a less forceful initial press, followed by increasing force as the task continued, till the sensor drop off at the end. In total, 63 repetitions were analyzed for the index finger, and 28 repetitions for the thumb. Both zoom-in and zoom-out gestures show that the shape of the index finger profile and at least one corresponding thumb profile are consistent with each other. This indicates that both the thumb and index finger move together during a zoom gesture. The curves also illustrate that participants applied more force when their fingers were further apart (at the start of the zoom-out task, and towards the end of the zoom-in task) compared to when they are closer together.

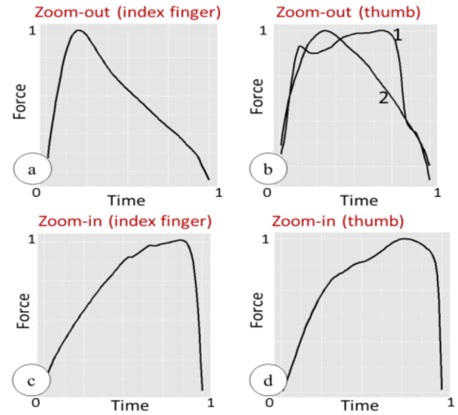

Figure 5: Profiles for (a) zoom-out using the index finger and (b) thumb, (c) zoom-in using index finger, and (d) thumb.

Summary

The study revealed consistent curves across all participants, which we were able to cluster together and develop high-level profiles that illustrate the characteristics of each touch gesture. Furthermore, the study confirmed our approach of analyzing touch input gestures and enabled us to carry out the next user study under different conditions.

INVESTIGATING FORCE AND CONTEXT

The second study aimed to investigate whether different conditions (or contexts of use) affect the force profiles developed in the first study, which involved a single and tightly-controlled condition. This enables us to make generalizable statements about the way in which users apply force whist carrying out touch gestures. It was anticipated that the shape of the profile curves would appear similar, however the different conditions are likely to cause variations in force and gesture completion times.

Selecting Conditions

Users perform touch-based gestures in a multitude of applications, devices, environments, and contexts. We chose a set of representative situations to form the characterization by situating each of these gestures into a series of generalizable conditions. These conditions are:

- Form factor (mobile phone vs. tablet): We hypothesized the trade-off between increased screen size vs. increased weight and awkwardness of device grasping will lead to study participants applying more force on the tablet.
- Interaction position (sitting vs. walking): The inherent nature of phones and tablets mean they are deployed in a range of static and moving contexts. We predict that input force would increase in non-static conditions as users compensate for the device vibrations associated with non-static interaction.
- Urgency (timed vs. untimed): Many game applications, as well as external environmental factors mean users

sometimes feel a sense of urgency to interact. We induce urgency by limiting task completion time and predict that study participants will apply more force in urgent conditions compared to non-urgent.

Experimental Setup

The web-based touch gesture application used in the first study underwent the following modifications: Firstly, the rotating task involved rotating an image to a specific orientation (replacing the targets – Figure 2g). Second, the zooming tasks involved resizing an image, rather than dragging two points to target locations (Figure 2h). Third, in the panning task users continued to pan until they found a specified keyword (Figure 2f). Finally, in addition to the Nexus 10 tablet, participants were supplied with a Nexus S mobile phone with a screen size of 4 inches.

In addition, we captured the six gestures under conditions where users feel a sense of urgency (e.g. whilst playing games). These tasks all included a timed and an untimed version. In the timed version, users are required to complete the tasks before a counter (displayed at the top of the application interface), which was intentionally kept to a low number to create a sense of urgency, reaches zero. The timed tasks were limited to: 20 seconds for typing, 5 seconds for zooming, 10 seconds for panning, 8 seconds for rotating, and 15 seconds for tapping.

Method

The user study consisted of a 2x2x2 factor design, which involved the form factor, interaction position, and urgency (see Table 1). The six gesture tasks were repeated in each condition. A within-subjects approach was used where each participant was exposed to the eight conditions. The conditions were counterbalanced using a Latin square and the order in which participants carried out the tasks was randomized. A different number of gesture repetitions were used by the participants to complete the tasks.

Table 1: Conditions explored in the 2nd study (C=Condition)

C1: tablet, walking, timed	C2: tablet, walking, untimed
C3: tablet, sitting, untimed	C4: tablet, sitting, timed
C5: phone, walking, untimed	C6: phone, walking, untimed
C7: phone, sitting, untimed	C8: phone, sitting, timed

Participants

We recruited 24 participants (12m, 12f), with an average age of 29.5 years. Each participant was rewarded with 8 GBP for each session, which lasted between 45 and 60 minutes. In general, all 24 participants were experienced with Smartphones and tablet devices. Only 7/24 participants were experienced with force sensing devices such as game controllers and Wacom tablets. Only one participant was left handed. Three participants stated that they believed the force sensing finger gloves reduced the responsiveness of touch events on the gesture application.

Procedure

Each participant was briefed on the study objectives and procedure, and asked to sign a consent form. Each trial involved a calibration phase, familiarization phase, and the experimental conditions. These are described below.

Calibration and Familiarization: Participants were asked to wear the force sensing equipment, which was calibrated in order to address individual differences in finger size and in the exertion of the baseline calibration force value (i.e. 464 grams). Once the sensors were calibrated, they carried out the six tasks on the web-application in a “test-mode” to become familiar with the application. Following this, participants completed each task once, in the untimed mode on the tablet and sitting down. Whilst participants were carrying out the tasks, the force readings were observed on the FingerTPS application to validate correct calibration.

Experimental conditions: Following the familiarization phase, participants were instructed to repeat the tasks under different the conditions described in the Experimental Setup. During the walking condition, participants walked in a figure 8 inside the room (approximately 8x4 meters). Once the experimental conditions were completed, participants were asked to fill in a short questionnaire to collect demographic data.

Results

Analysis of Force Profiles

The focus of this study is twofold; firstly we compare the profiles constructed in the first study with the second study as a means of validating and revising our models. We then examine the variations in force levels and time taken to complete the gestures in the different conditions. We also report the average forces exerted and the average gesture completion times for all conditions, including density plots that illustrate common ranges of these forces and times. We adopted the same procedure in processing the data for each gesture task as described in the first study (i.e. preprocessing, thresholding, normalization, interpolation, clustering, and averaging).

Typing: It was clear from the analysis that the force profile for typing (Figure 6a) indicated a more rapid increase to the peak force, followed by the sensor drop-off. Thus, participants in study 2 were pressing for shorter periods of time. The difference between the typing profile from study 1 and the profiles for each condition in study 2 ranged from 9.78% to a maximum of 17.79%. As these differences are relatively significant, a revised profile curve (with a steeper slope to the peak force) for the typing gesture is proposed (Figure 6d). In total, 5939 repetitions were analyzed in study 2 and we found that the curves across all the conditions were highly similar in shape.

Panning: The panning gesture profiles that emerged from the second study revealed relatively high differences compared to the profile from study 1(ranging from 14.73%

to 18.49%). Figure 6b shows, for instance, that the sensor drop-off occurs further away from the peak, thus indicating a dragging action. A revised panning profile is therefore provided (Figure 6e) which shows a plateau around the peak force region. In study 2, participants were looking for a specific keyword, therefore it was expected that participants would combine a flicking action with a dragging action to verify that they have found the keyword. The panning gesture consisted of 2657 repetitions in total across the 8 conditions and there was little difference of profile curves in between the conditions.

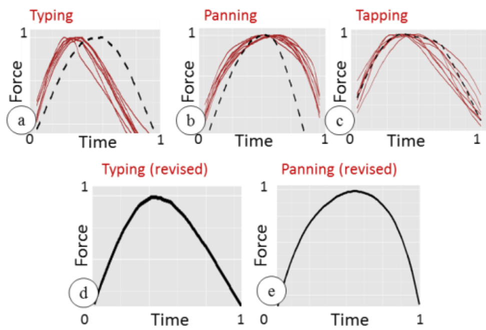

Figure 6: Dotted lines represent study 1 curves. Each solid line represents a condition in study 2: (a) typing, (b) panning, (c) tapping, (d) revised typing profile, (e) revised panning profile.

Tapping: The tapping gesture profile from study 1 provides a suitable representation of study 2 results, with differences ranging from 2.33% to 8.66%. The tapping curves from study 2 (Figure 6c) indicated a quick press with a small delay once peak force was reached (i.e. users typically waited for feedback before releasing a tap interaction). A total number of 1661 repetitions were analyzed.

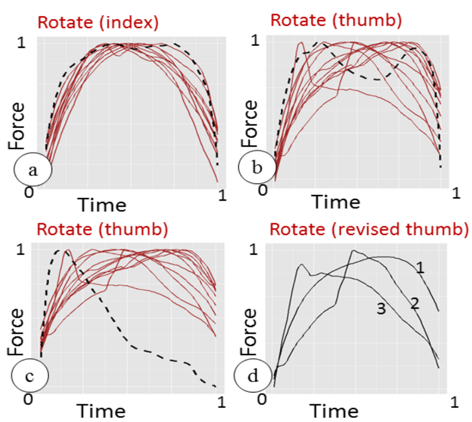

Figure 7: Dotted lines represent profile curves from study 1. Rotate profile curves (solid) from study 2 for (a) index finger, (b) and (c) thumb and (d) revised thumb profiles for rotate.

Rotating: Figure 7a illustrates that the index finger profile from study 1 closely fits the curves generated in study 2 (with differences ranging from 5.4% to 14.27%). The profile indicates a sharp increase to peak force (Figure 7a), the continuation of the gesture with slight variations in force and followed by the sensor drop-off. A total of 1377 repetitions were analyzed for the index finger. All curves across the 8 conditions were also highly similar. In contrast, the thumb produced higher variation (Figure 7b and 7c) across the 8 conditions (ranging from 11.2% to 42.12%). Therefore, the two profile curves from study 1 do not adequately represent the thumb in a rotate interaction. As a result, a set of three profile curves are proposed (Figure 7d). The maximum difference between the three revised curves is 13.21%. Although the differences are not significantly high, it is clear that the shapes are distinct. Curve 1 consists of a smoother interaction where participants press on the device in a highly controlled manner. Curve 2 involves a rapid increase in force (i.e. a hard press) followed by gradually lifting off from the device. Finally, curve 3 begins with a softer press until peak force is reached, followed by a relatively steep decrease in force. In total, 1191 repetitions of the thumb were analyzed.

Zooming-In: The index finger curves across the 8 conditions (Figure 8) were highly similar in shape to the corresponding profile from study 1 (differences ranging from 5.2% to 12.95%).

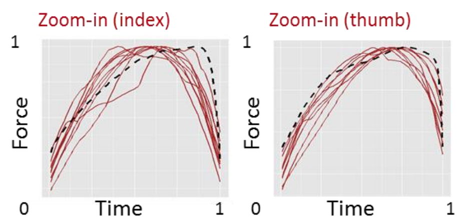

Figure 8: Dotted lines represent profile curves from study 1. Zoom-in profile (solid) curves from study 2 for (left) index finger, and (right) thumb profile.

It shows a gradual increase to peak force and to the end of the gesture, followed by the sensor drop-off. Similarly, the thumb analysis revealed a low level of variation compared to the thumb profile curve from study 1 (ranging from 2.94% to 12.13%). The thumb profile is also consistent with the index finger, with a gradual increase in force over time. A total of 1192 repetitions were analyzed for the index finger, and 983 for the thumb.

Zooming-Out: The profile curves for the index finger zoom-out gesture derived from the 8 conditions in study 2 (Figure 9a) were highly distinct to the profile curve presented in study 1 (differences ranging from 18.33% to 29.14%). The profile from study 1 shows an initial hard press, followed by gradually decreasing force. However, study 2 curves show a hard press which plateaus around the peak force region, indicating that participants pressed and held for longer. Therefore, a revised profile curve for the index finger is proposed (Figure 9d). The analysis for the thumb showed relatively high variation in comparison to curve 1 from study 1 (ranging from 9.12% to 23.15%) and a higher variation compared to curve 2 from study 1 (9.82% to 30.06%). As a result of these differences, two revised profile curves are proposed. Curve 1 shows a rapid increase in force to the peak force, and curve 2 shows a slower increase in force. In total, 1061 index finger repetitions and 911 repetitions for the thumb were analyzed.

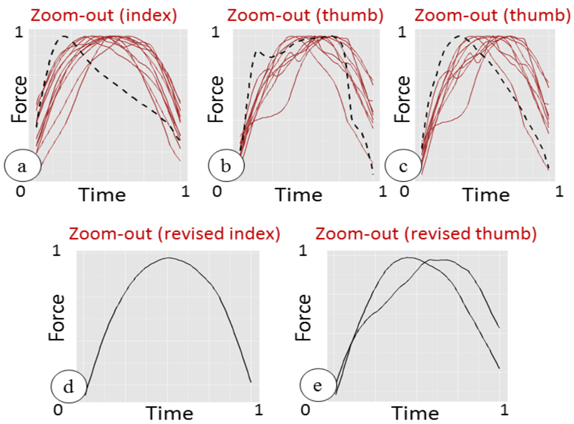

Figure 9: Dotted lines are profiles from study 1. Zoom-out profiles from study 2 for (a) index finger, (b) and (c) thumb and revised profile curves for (d) index finger and (e) thumb.

Effect of Conditions on Force and Time

To investigate whether the different conditions had an effect on time and force, we carried out multiple factor regression analysis on each of the gestures to determine which factors had significant effects. Each condition had three factors, which were form factor (mobile vs. tablet), position (sittings vs. walking) and urgency (timed task vs. untimed task).

Typing: Participants typically applied more force on a tablet ($F_{1,6537}$=178, p<0.001) or under urgency-induced tasks ($F_{1,6537}$=21.9, p<0.001). In terms of interaction length, participants typically pressed for longer durations on the mobile phone ($F_{1,6537}$=6.98, p<0.01).

Panning: Participants exerted more force on the tablet ($F_{1,2655}$=19, p<0.001), and whilst they were walking ($F_{1,2655}$=22, p<0.001). Panning repetitions were also longer in duration on the mobile phone ($F_{1,2655}$=92.2, p<0.001).

Tapping: Force variations for tapping were caused by position ($F_{1,1659}$=3.93, p<0.05), where less force was generally exerted whilst participants were sitting down.

Rotate: Participants applied less force whilst sitting (thumb: $F_{1,1189}$=5.91, p<0.05; index finger: $F_{1,1374}$=11.8, p<0.001) and also less force on the phone (thumb $F_{1,1189}$=3.11, p=0.078; index finger: $F_{1,1374}$=16.1, p<0.001).

Zoom-out: For zoom-out, participants pressed harder on the phone with their thumb ($F_{1,909}$=27.3, p<0.001) and harder with their index finger whilst walking ($F_{1,1059}$=22.4, p<0.001). Participants spent longer zooming-out on the mobile phone with their thumb ($F_{1,909}$=4.02, p<0.05).

Zoom-in: Participants exerted more force with their thumb on the phone ($F_{1,997}$=16.7, p<0.001) but with less force using their index finger ($F_{1,1190}$=8.62, p<0.01). Participants also applied less force with their index finger whilst sitting ($F_{1,1190}$=13.4, p<0.001). Participants spent longer with their thumb on the phone ($F_{1,997}$=3.6, p<0.05).

Distribution of Force and Time

To provide a general understanding of gesture force and time, Table 2 displays the averages for all gestures, and Figure 10 (on the next page) displays density plots showing the distributions of peak forces and gesture completion times. The force and time values in this case were not normalized. We found that the distribution of peak forces and completion times were highly skewed to the right (see Figure 10, next page), therefore we report the interquartile (i.e. between 25% and 75% of the distribution) mean as a measure of central tendency, and the interquartile range (IQR) as a measure of spread. These are shown in Table 2.

Table 2: IQR Mean force and time for gestures and conditions with range in brackets Mean=$\bar{x}$, T=thumb, I=index finger

Gesture	Force (grams)	Time (milliseconds)
Typing	$\bar{x}$: 41.53 (20.37, 73.09)	$\bar{x}$: 119.66 (100, 150)
Tapping	$\bar{x}$: 69.05 (22.72, 163.9)	$\bar{x}$: 188.69 (125, 300)
Panning	$\bar{x}$: 55.16 (26.17, 96.16)	$\bar{x}$: 233.65 (150, 350)
Rotate	**T**: $\bar{x}$:15.74 (3.86, 40.2) **I**: $\bar{x}$: 32.46 (9.81, 72.8)	**T**: $\bar{x}$: 300 (150, 450) **I**: $\bar{x}$: 288.12 (150,450)
Zoom-In	**T**: $\bar{x}$: 33.81 (2.73, 69.6) **I**: $\bar{x}$: 54.96 (11.37, 103.78)	**T**: $\bar{x}$: 292.38 (150, 450) **I**: $\bar{x}$: 274.64 (150, 425)
Zoom-Out	**T**: $\bar{x}$: 28.03 (4.49, 98.97) **I**: $\bar{x}$: 45.56 (13.36, 131.99)	**T**: $\bar{x}$: 294.44 (150, 450) **I**: $\bar{x}$: 274.64 (150, 425)

In general, rapid entry tasks like typing show that the mean force and gesture completion time were much lower compared to other gestures. Tapping and panning show higher force and time values indicating slower presses caused by awaiting confirmation of a tap or searching for a keyword in a list. It is likely that the higher mean force in tapping was caused by the occasional unresponsiveness of the gesture where participants would press harder if an initial tap was unregistered by the gesture application. For two-finger gestures such as rotating and zooming, the mean forces exerted were generally low whilst the mean times were higher than typing, tapping and panning. The index finger exerted more force than the thumb gestures, which denotes its dominance during two-finger gestures.

For illustrative purposes, the density distributions (Figure 10) show 95% of all force and time values for each gesture, including dotted lines that show the interquartile range. The upper section of the plots show the distribution of force values and the lower section show the distribution of gesture completion times. The plots indicate that although there is variation between the conditions for each gesture, there are commonalities in the general range of force exerted, and the general time taken to complete the gestures. Thus, forces and completion times outside this range are uncommon, e.g. the forces for typing vary across conditions, but fall within a range of 0 to 150 grams.

DISCUSSION

The two user studies described in this paper presented a number of insights that characterize touch gesture input force on mobile devices. It was evident from the gesture profiles of both studies that typing and tapping gestures consisted of quick presses. The panning gesture illustrated a plateau in the peak force region, indicating a dragging action and continuous (as well as consistent) application of force. In contrast, continuous gestures such as rotating and zooming produced more variable forces over time. The index finger profiles for rotate, zoom-in, and zoom-out showed consistency across all the conditions in contrast to the thumb profiles, which produced more variation. There was a higher degree of control with the index finger in the gesture interactions compared to the thumb. This is also reflected in the force variation analysis where we found that participants applied more force with their index finger for the rotation and zooming gestures.

Force variations were mainly affected by the form factor and interaction position, which contrasted our prediction that urgency would cause the most variation (i.e. participants would press harder under time pressure). Participants generally pressed harder on the tablet whilst typing, panning, rotating, and with their index finger for zooming. We believe that participants compensated for the weight of the tablet and exerted more force. Participants also took longer to complete typing, panning, and zooming gestures on the mobile phone. It is likely that the smaller screen size of the phone caused participants to be more precise in carrying out gestures. For instance, pressing the right letters on a touch keyboard requires more precision on a smaller screen. Similarly, participants were likely to press-and-hold for longer during panning tasks to ensure the searched keyword was in view. The interaction position affected tapping, panning, rotating, and zooming gestures, with participants applying more force whilst walking. This matched our prediction where participants press harder to compensate for device vibrations caused by movement. Urgency only affected the typing gesture, i.e. more force was applied under urgency-induced conditions. The density plots (Figure 10) provide general ranges that the design of force-sensitive devices which integrate standard touch gestures can adopt. We found that forces and completion times above these ranges, for instance, were uncommon.

Implications and Usage

The results in this paper can aid designers of touch screen, flexible display, and force-sensitive surfaces by enabling them to differentiate between gesture inputs (tapping, pinching, zooming, rotating) and force inputs (e.g. tapping harder to achieve a different result than a key-press). For instance, the density plots (Figure 10) shows that it is uncommon to apply forces above 150 grams for the typing gesture. Our findings can also help calibrate such devices such that the gestures adhere to the force and time ranges shown in Figure 10. The differences found between forces applied on mobile and tablet devices can also inform designers that a higher force tolerance must be included for larger devices (tablets) for standard touch gestures. The force profiles of the studied gestures can be used to aid gesture recognition in force-sensitive surfaces (e.g. a force sensitive surface that indirectly controls content through touch gestures). Our studies showed that, for instance, whilst a typing gesture is a simple increase and decrease in force values, a rotation gesture consists of varying forces.

Limitations

The findings of our user studies are based on a specific set of devices (i.e. Nexus S phone and Galaxy 10 tablet) and a specific application (i.e. the touch gesture application). However as Smartphones and tablet devices with capacitive touch screens are commonplace, we believe that our results are generalizable to similar devices. The gesture application was designed for standard gesture tasks; however the FingerTPS equipment was somewhat restrictive in that participants were only able to use their fingers that were attached with the force sensors (e.g. users might choose to type with multiple fingers). Furthermore, the data capture rate of the FingerTPS equipment was relatively low (40 Hertz), thus limiting the sample points in each repetition. A higher data capture rate, for instance, would have enabled higher granularity when plotting the curves (i.e. better indications of where force variations might occur). Furthermore, there are numerous avenues for future characterizations including tests for the influence of device lag, different contents and contexts, typing with various fingers, and using clock-wise rotations.

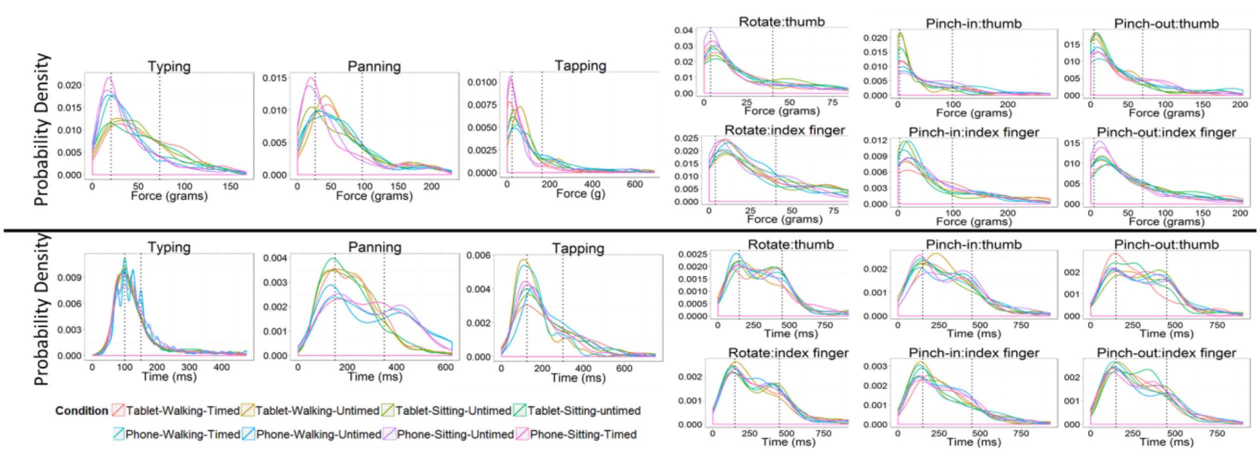

Figure 10: Density plots showing distributions of force (top row) and time (bottom row).

CONCLUSION

In this paper we presented a characterization of force input for standard touch gestures on mobile devices by carrying out two user studies. The studies investigated: (1) force profiles that depict typing, panning, tapping, zooming, and rotating gestures, (2) the effect of different conditions on force exerted and time spent completing these gestures, and (3) common force and gesture completion time ranges. Our contributions included profiles of each gesture which indicate that typing and tapping gestures were consistently short presses whilst panning involved a dragging action. Two-finger gestures such as zooming and rotating revealed higher consistency and control for the index finger, and high variability in force over time for the thumb. It was also evident that force and gesture completion time was mainly affected by form factor and interaction position. The gestures were longer on the phone, more force was applied on the tablet, and more force was applied whilst participants were walking. Further, despite the variations between conditions, participants applied force and completed tasks within specific force/time ranges. This characterization aims to enable designers of interactive mobile devices to integrate force and standard touch gestures to augment interactivity, as well as design for different conditions.

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