Evaluating Effects of Structural Holds on Pointing and Dragging Performance with Flexible Displays

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ABSTRACT

In this paper, we present a study of the effects of structural holds and rigidity of a flexible display on touch pointing and dragging performance. We discuss an observational study in which we collected common holds used when pointing on a mockup paper display. We also measured the force patterns each hold generated within the display surface. We analyzed this data to produce 3 force zones in the display for each of the four most frequently observed holds: the *grip* zone, *rigid* zone, and the *flexible* zone. We report on an empirical evaluation in which we compared the efficiency of pointing and dragging operations between holds, and between structural zones within holds, using a real flexible Lumalive display. Results suggest that structural force distributions in a flexible display affect the Index of Performance of both pointing and dragging tasks, irrespective of hold, with rigid parts of the display yielding a 12% average performance gain over flexible areas.

ACM Classification H5.2 [User Interfaces]: Interaction styles.

Author Keywords Organic User Interfaces, Flexible Displays, Fitts' Law.

General Terms Experimentation, Human Factors.

INTRODUCTION

With the recent development of flexible display technologies, such as Flexible E Ink [3], Flexible Organic LEDs (FOLEDs) [1] and Lumalive displays [9], come new challenges for the development of touch screens. While touch input in rigid Liquid Crystal Displays (LCDs) has matured to mass-market adoption, issues exist, both technical and user-related, that may impede adoption of touch in flexible displays. One immediate issue is that flexible displays, unlike rigid screens, give way: flexible displays may not always provide a sufficient normal force to support the fingers when touching. A second, and related, issue is that the distribution of normal forces in a flexible display may depend on the way the display is held: different supporting holds may produce different force curves in the display. Such curves may provide structural support during pointing tasks on flexible substrates, such as paper. A compounding issue here is the presence of a bezel. In rigid tablet PCs, such as the Apple iPad, large bezels are used to prevent the holding hand from spuriously activating the touch inputs while holding. Because holding a bezel of a flexible display may not provide an evenly distributed normal force throughout the display, users might need to hold the screen beyond its bezel, potentially triggering spurious touches. One question then, is whether users of flexible displays can produce a sufficient distribution of normal forces in the display surface while holding only the edges of the display. Despite the above issues in developing touch inputs for flexible display interfaces, we believe there is one compelling reason why flexible displays, particularly, Flexible E Ink, will be adopted: they allow for user interfaces that closely mimic the easy of use of paper documents. According to Sellen and Harper [13], there are a number of distinct advantages of paper documents over traditional windowed computer interfaces. The superior contrast and infinite battery life of paper documents aside:

(1) Paper is thin, low-weight, yet rugged, allowing superior portability over any current mobile computing form factor.

(2) Paper can have many different form factors and sizes. This allows for distinct physical affordances [8] that relate to specific functionalities: reading a newspaper serves a different purpose than reading a product label, and these distinctions are evident through those form factors.

(3) Paper is flexible in shape, which provides ergonomic benefits and adjustment of screen real estate size to the context of use. Users are adept at reading paper documents in different physical contexts, independently of the size of the document. This is because they can fold paper documents such as a maps or newspapers into a size or form that befits space limitations.

(4) Most rigid UIs, the iPad no exception, also rely on input that is dependent on visual rather than tactile cues. By contrast, paper is both tactile and kinesthetic.

(5) In Graphical UIs, input is typically limited to a single display, making interleaving, retrieving and organization of information relating to multiple tasks a sequential process. By contrast, paper documents can have many *"displays"*, with each display pertaining only to a specific and physically delineated task context.

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Paper does have one obvious downside: it cannot be dynamically rewritten. Flexible display technologies such Flexible E Ink are now changing this, allowing the navigational benefits of paper documents to be combined with the dynamical display characteristics of computers. But before digital paper receives widespread market adoption, we will need to advance our techniques and technologies for (multi)touch input on flexible screens.

In this paper, we present a first step in this direction: an empirical study aimed at exploring the relationship between flexibility of the display and the efficiency of pointing at specific locations on the display. We examine these aspects in light of different holding patterns producing force differentials in the display that alter its rigidity, and thus its performance.

RELATED WORK

There is a significant body of research on flexible sensors, but there appears to be little work on evaluations of their performance. SmartSkin by Rekimoto [10] was one of the first papers to demonstrate the potential for capacitive (multi)touch sensors in flexible form factors. Rosenberg et al. [11] discuss the unMousePad, (now Touchco [14]), a touch-sensitive flexible surface capable of measuring multi-touch pressure signatures. It is one of only a few flexible multi-touch input devices available on the market. Another capacitive flexible touch technology is Displax [2], which has mostly been applied to rigid displays. To our knowledge, these technologies have yet to receive formal usability assessments as flexible input devices.

Flexible Computers

Schwesig et al. [12] produced one of the first mockups of a small credit-card sized computer that involved physical deformation of its surface. Navigation was achieved through bending the display, e.g., to zoom in and out of information. Authors did not provide an evaluation. In PaperWindows, Holman et al. [5] simulated the use of flexible display surfaces for page navigation by augmenting real paper with projected images. This was accomplished by tracking the shape and location of paper documents as well as fingers using Vicon motion capture. While their system and tracking techniques are very similar to those deployed in our work, the authors did not report on a quantitative study. Lee et al. [6] discussed one of the few user studies of deformable (mockup) displays. In their experiment, they asked users to create and perform bend gestures for future flexible displays, using paper, plastic and textile mockups. They found a significant time difference in planning time for gesture design between cloth and plastic displays. They also found that the non-dominant hand played a supporting role, while the dominant hand performed most interactions on the middle of the right side of the material. We were inspired by this work for our first study. Similar in nature, Watanabe et al. [16] discussed Bookisheet, a set of flexible input devices made out of sheets of thin acrylic augmented with bend sensors. Bookisheet could simulate the turn of pages through bends. However, their evaluations focused on the use of various bend gestures for interactions, rather than pointing.

Fitts' Law for Display Evaluation

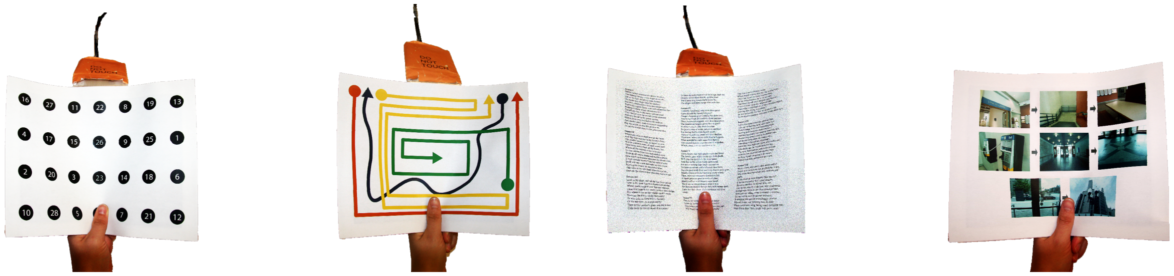
We cannot possibly do justice to the large body of work on Fitts' Law in this review. However, much of the work is geared towards gauging effects of input devices on pointing and dragging performance [7]. In one of the original evaluations of dragging performance, MacKenzie et al. [7] found values of 4.5 bits/s for pointing, as compared to 4 bits/s for dragging with a mouse. We did not find related work on Fitts' Law evaluations comparing areas of display. Zhai [17] discusses differences in performance between manipulations of the fingers, hand and wrist in an experiment where he utilized a glove and a FingerBall in a six degree of freedom VR docking task. He concluded that small muscles groups, such as fingers, have performance advantages over large muscle groups. Wang et al. [15] evaluated finger input for multitouch interactions. Their work centers on the "fat finger" problem: the size of the finger in relation to the accuracy of touch. Wang found that the index, middle and ring finger give a higher input precision than other fingers. Guiard [4] explained differences between non-dominant and dominant hand performance with his Kinematic Chain theory. According to him, the non-dominant hand typically provides the context to the dominant hand, e.g., by holding a piece of paper, or a display, while the dominant hand provides the action component, e.g., pointing at the display.

STUDY 1: OBSERVATIONAL STUDY

In order to better understand how the non-dominant hand provides support for pointing on flexible surfaces, and to obtain insight into the kind of supporting holds that exist, we designed an observational study into the ways in which users might hold flexible displays in various tasks.

Observing Holds

Our study was designed as a field study in which users were asked to perform representative tasks in real world conditions. We wanted to introduce as little technology as possible, so as to allow as rich an environment for discovering potential holding behavior as possible. To avoid damage to our flexible display, we deemed the use of a simple printed paper mockup sufficient for this open-ended study. We did require some electronic way to record various holding patterns during the field study, as the use of video alone was insufficient: Camera placement was an issue, and video would not allow us to record force differentials in the display surface between holds. To be able to reliably measure holds and folds on the display surface, we deployed a pressure sensitive film called Touchco [14] in most tasks, details of which are outlined in the *Apparatus* section.



(1) Pointing *(2) Tracing* *(3) Reading* *(4) Mobile Navigation*

Figure 1. Four tasks, printed on a paper mockup display mounted on a Touchco flexible multitouch pressure sensor.

Selecting Tasks

In selecting task scenarios for our observational study we were inspired by mobile applications. We wanted our tasks to be generalizable, yet sufficiently specific for users to be familiar with. For this reason, we included a basic pointing task in our observational study, in which users were asked to point at a random number, printed on a mockup paper display (Fig. 1.1). A second basic task was dragging. Dragging involves pointing at a target, selecting it by touching, moving the finger to a second target location, then releasing. The simplest way to model this task without interactive graphics was to print lines on paper, asking participants to trace these lines from start to finish (Fig. 1.2). Since tablets are commonly used for reading, we wanted to include a reading task as well (Fig. 1.3). Finally, we decided to include a way-finding task in which participants needed to hold the display while walking through a building (Fig. 1.4). A requirement for the first study was that tasks were executed in a number of different postures, in particular, while standing, sitting and walking. Because of the logistics involved, and because our participants spent a significant amount of time in this locale, we chose a public lounge with large leather couches, hardwood chairs, soft leather study chairs, soft foam cushions, and carpeted areas, rather than a participant's home.

Apparatus

We used a printed US Letter paper mockup display sandwiched with a sheet of 8.5" *x* 11" Touchco (see Figure 1) [14]. Touchco is a pressure sensing flexible multitouch device consisting of 5 layers: a layer of parallel wires, a Force Sensing Resistor (FSR), a layer of air, another FSR and a second layer of parallel wires that are perpendicular to the top layer. It is approximately 0.25 mm thick. Touchco has a resolution of 100 dpi and is capable of sensing forces from .05 N to 50 N. We used this information to create a pressure map for each hold. A video camera was used to record additional footage of the participant holding the mockup display. In the mobile task, we used a head mounted camera to observe the participant holding the display, while a second camera recorded the 3rd person view. During each of the tasks, we marked recordings every time a unique holding gesture or change in posture occurred, which eased subsequent analysis of both video and Touchco data. A rigid backing that could easily be attached and removed was used to check for differences in holding styles between flexible and rigid displays. Note that the Touchco had to be held in landscape mode because of the connector interfering with holds; we corrected for any potential skew this caused in our data for our second study.

Tasks

Figure 1 shows each task printed on a different sheet of paper. Participants conducted each task, in random order, in both rigid and flexible conditions.

(1) Pointing

For this task, the Touchco was overlaid with a sheet of 28 printed numbers, as shown in Fig. 1.1. Participants were asked to listen to an audio file listing a series of random numbers. They were instructed to touch the display in the location associated with each number. During the task, we instructed the participants to hold the interface in the most comfortable way, while standing.

(2) Tracing

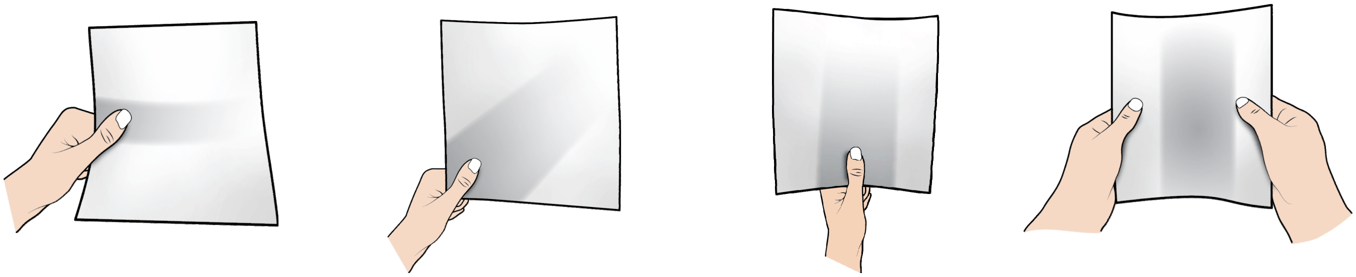
To simulate dragging, we asked participants to trace a line from a circle to a triangular symbol printed on the mockup paper display overlaid on the Touchco (Fig. 1.2). These lines covered all areas of the screen in several orientations (left, right, up, down, diagonally, straight and curved). As in the first task, the participants were instructed to hold the display comfortably while standing.

(3) Reading

The third task was a reading task (Fig. 1.3). In this task, we instructed the participants to find a location in the room and make themselves comfortable while seated, to read a single page of Shakespeare's *Sonnets* off of a mockup paper display overlaid on the Touchco.

(4) Mobile Navigation

We requested participants to walk through a building while holding the mockup display. They were required to navigate to a series of locations indicated by a set of pictures on the display (Fig. 1.4), and asked, as a distractor task, to copy down a number placed in those locations on a notepad with a pen. The path was approximately 150 *m* long and started indoors and ended outside. It utilized one



(a) Vertical Center (b) Bottom Corner (c) Bottom Center (d) Bi-manual

Figure 2. The four common holds observed using a mockup display during our first study: (a) hand in the vertical center, (b) hand at the bottom corner, (c) hand in the bottom center, and (d) bi-manual. Gray zones indicate corresponding structural forces.

staircase and three doors. We did not measure force patterns with Touchco in this task as it was insufficiently portable.

Participants

We used 8 participants, mean age 21.3, 4 females, 4 males.

OBSERVATIONAL STUDY: DISCUSSION

We analyzed Touchco data, with video recordings serving as a visual reference to identify holds, between markers in our data recordings. We then calculated frequency of use of each hold for each task as a mean percentage of overall hold time during which that hold was deployed. The 5 most frequently deployed holds are listed below, with frequency of use per task, for both flexible and rigid conditions:

a) **Vertical Center** (Fig 2*a*). Left or right non-dominant hand holding the center of the display, left or right. Pointing *(rigid 10%),* Tracing *(flexible 27%, rigid 21%),* Reading *(flexible 30%, rigid 30%)* and Mobile Navigation *(flexible 17%);*

b) **Bottom Corner** (Fig 2*b*). Left or right non-dominant hand holding the bottom corner of display, left or right. Pointing *(flexible 9%, rigid 17%),* Tracing *(rigid 15%),* Reading *(flexible 13%)* and Mobile Navigation *(flexible 30%, rigid 38%);*

c) **Bottom Center (**Fig 2*c*). Left or right non-dominant hand holding the bottom center of display. Pointing *(flexible 87%, rigid 47%),* Tracing *(flexible 73%, rigid 31%),* Reading *(flexible, 12%, rigid 12%)* and Mobile Navigation *(flexible 49%, rigid 55%);*

d) **Bi-manual** (Fig 2*d*). Both hands holding vertical center of the display on each side. Pointing *(flexible 3%, rigid 10%),* Reading *(flexible 33%, rigid 51%),* Mobile Navigation *(flexible 6%, rigid 6%);*

e) **Flat** (not shown). Display placed on surface of the flat left or right non-dominant hand. Rigid only, Pointing *(8%),* Tracing *(31%).*

Differences Between Tasks

There were some marked differences in the use of holds between tasks. Most notably, in pointing and tracing all holds were one-handed. E.g., the reading task frequently involved *Bi-manual* holds, while in mobile navigation tasks users preferred a *Bottom Center* hold.

(1) Observations in the Pointing Task

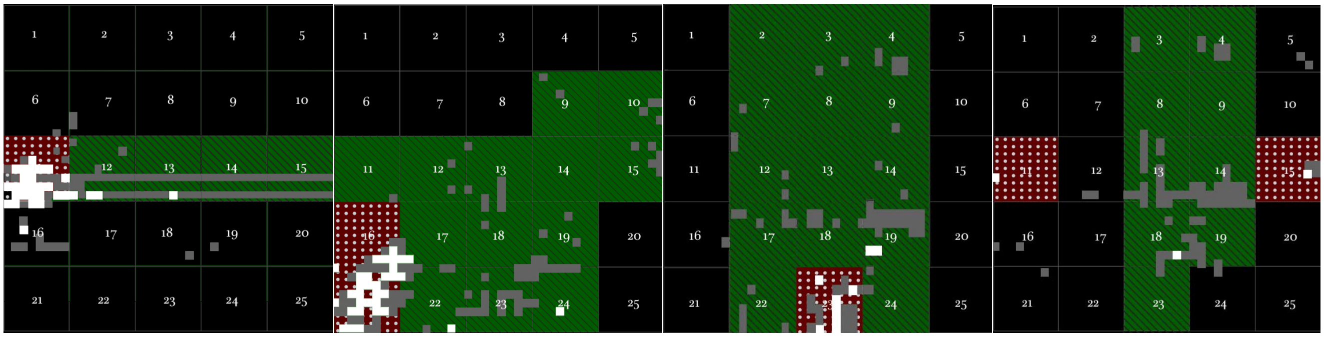
In the flexible condition, 87% of the holds used in pointing consisted of a hold in which the display was held up with the non-dominant hand at the *Bottom Center* (Fig 2*c*). We believe the prevalence of this hold was due to it producing a relatively pronounced structural fold through the y-axis of the display, which radiates an even normal force through the horizontal center of the display. At 9%, the second most popular flexible hold was with a non-dominant hand in the *Bottom Corner* (see Fig 2*b*). Here, force fields radiate diagonally through the display. A *Bi-manual* hold (see Fig 2*d*) was performed in 3% of cases, alternated with one of the one-handed holds. In the rigid condition, participants used *Bottom Center* 47% of cases. A *Bottom Corner* hold was used in 17% of cases, and *Vertical Center* (Fig 2*a*) and *Bi-manual* holds each in 10% of cases. They also deployed a *Flat* hold in 8% of cases, where the display was placed on top of a flat non-dominant hand. We observed more variety and alternation of holds in the rigid condition, with participants moving back and forth between a bi-manual hold and a one-handed hold between trials, presumably due to fatigue. Infrequently, when the target was located near the bezel, we observed participants alternating a *Bi-manual* hold with a pinch gesture to select the target without releasing the display.

(2) Observations in the Tracing Task

In our tracing task, we observed participants using three different holds. In the flexible condition, at 73%, the most frequent hold was the non-dominant hand holding the *Bottom Center*. At 27%, the second most frequent hold was at the *Vertical Center*. In the rigid condition, results were evenly split. In 31% of cases participants used the non-dominant hand holding the side of the display at the *Bottom Center*. In 31% of cases, participants used a hold in which the display was placed on top of a *Flat* non-dominant hand. In 21% of cases participants held the display at the *Vertical Center*, and in 15% of cases at the *Bottom Corner*. Some participants deployed a bimanual hold between traces, likely to provide a force counteracting friction on the display surface. When a drag interfered with a hold, participants either relocated their thumb or switched holds.

(3) Observations in the Reading Task

At 33% of flexible and 51% of rigid cases, the most frequently observed hold while reading was a *Bi-manual* hold in which the display was held in the vertical center on both sides. We believe this hold provided the most stability with the least energy expenditure. We found participants



(a) Vertical Center *(b) Bottom Corner* *(c) Bottom Center* *(d) Bi-manual*

Figure 3. Force heat maps for the 4 most common holds found in the observational study: Vertical Center, Bottom Corner, Bottom Center, and Bi-manual. White, gray and black areas respectively indicate high, medium and low-pressure zones measured over all tasks. Dotted (*red*), hatched (*green*) and black areas indicate grip, rigid, and flexible structural zones for which performance was compared in our second, controlled study. Numbers correspond to locations used as targets in pointing tasks.

resting elbows, and bottom parts of their display, on their lap or table while holding, in both rigid and flexible conditions. For both conditions, at 30%, the second most frequent hold was the non-dominant hand placed at the *Vertical Center*. For flexible, the *Bottom Corner* hold was also used in 13% of cases. For both flexible and rigid conditions, *Bottom Center* was used in 12% of cases. Participants with flexible displays deployed a larger variety of holds and postures. Participants sitting at a table, in an upright position, preferred to hold the display bi-manually. Participants sitting in a lounge chair in a more relaxed position tended to hold the display with a non-dominant one-handed hold, while using a body part to prop up the other side of the display.

(4) Observations in the Mobile Navigation Task

In our mobile navigation task, the participants were given complete freedom of movement. The majority of our participants were, however, consistent in the way they held their paper display, irrespective of rigidity. At 49% of flexible and 55% of rigid usage cases, the most frequently observed hold was where the non-dominant hand held the *Bottom Center* of the display. The *Bottom Corner* hold was the second most popular at 30% of flexible and 38% of rigid cases. In flexible conditions, 17% of cases was a *Vertical Center* hold. Bimanual holds were observed in 6% of cases for both rigid and flexible. When taking notes, participants changed holds. In the rigid condition, participants used the display as a surface for their notepad. In the flexible display condition, they would hold the display either with the same hand as the note pad, while letting it dangle, or they would put the display in their pocket.

STUDY 2: EXPERIMENT DESIGN RATIONALE

For our second study, we designed a controlled experiment that measured the effect of the identified holds, as well as differences in structural integrity caused by these holds, on pointing and dragging tasks using a real flexible display.

Selecting Holds for the Experiment

Together, the five observed holds accounted for over 93% of all observed hold cases. Since the *Flat* hold only occurred with rigid displays, we selected the other four holds for our second study. Since all of the participants in the second study were right-handed, and applications of holds appeared identical, but mirrored, for left and right-handed versions, we selected only left-handed versions of holds. This led to a shortlist of the four holds in Figures 2 and 3: *Vertical Center; Bottom Corner; Bottom Center;* and *Bi-manual*.

Relating Holds to Structural Areas of the Display

After classifying Touchco data as pertaining to one of these four holds, we calculated the average force deployed by each of the four holds, for each of 25 locations on the Touchco, over all participants. Numbers identify these 25 locations laid out as a square in Figure 3. We performed a linear geometrical transformation along the horizontal axis to fit the 8.5”*x*11” Touchco grid into an 8.5”*x*8.5” square, such that it would correspond to the dimensions of the flexible display used for our second study. For each hold, Touchco force differentials provided us with insights as to the normal forces generated, allowing us to identify where the display was being held, and where the areas with the highest rigidity and flexibility might be. Figure 3 shows force heat maps for each hold across the 25 locations. We thresholded Touchco pressure data, averaged across participants, to produce three distinct force levels: 0-33% of maximum force (black in Fig. 3); 33%-66% of max. force (gray in Fig. 3) and 66%-100% of max. force (white in Fig. 3), where maximum force was normalized over all recordings. We then overlaid the 25 locations, assigning locations to structural zones of the display as follows: locations with more than two white pixels were tagged as *grip zones*, i.e., where the thumb was holding the display (dotted/red areas in Fig. 3) and locations with more than 2 gray pixels as *rigid zones*, i.e., where structural folds occurred (hatched/green areas in Fig. 3). The remaining locations were tagged as *flexible zones* of the display (black areas in Fig. 3), for each hold. We used this assignment of structural areas for each hold to analyze the performance of rigid vs. flexible areas of the display in our second experiment.

Flexible Display

To study the effect of holds in the proper context of an interactive display, we needed to deploy a real flexible display in this experiment. Rather than simulating a flexible display through projection, we chose the Philips Lumalive [9] LED display. This display was the only available flexible display technology approximating US Letter size that was available at the time of this study. One of the drawbacks of Lumalive over other methods is its relatively slow response time, and relatively low resolution. However, we believed the results of the study would be more generalizable by using an actual flexible display.

Task Selection

We decided against using the reading task, as it did not involve any real interactivity. We also could not use the mobile task as it was too difficult to obtain measurements while users were walking through a space. We thus limited our empirical study to tasks 1 and 2, pointing and tracing (i.e., *dragging*), two of the most basic tasks performed in GUIs [7].

Problems with Flexible Touch Input

We also decided not to use Touchco as an input device in the second study. While Touchco works well for identifying holding patterns that exert sufficient pressure on the material, the normal forces exerted by the Lumalive display were not sufficient to obtain a reliable signal from the pressure sensitive surface during pointing. A second flexible touch technology that we considered was Displax [2]. Displax consists of a capacitive touch film that is extremely thin, transparent and flexible. It is extremely sensitive to any single touch. When tested, it was very difficult to hold the display without also triggering input on the Displax. Additionally, sensitivity to the supporting hold rendered large parts of its input grid unusable. A bezel would not have solved this problem as the capacitive field was too strong to shield effectively.

Input on Flexible Displays is Inherently 3D

Another important consideration in determining a suitable tracking technology for our formal study was the observation that finger movement on flexible displays is mostly not two-dimensional: When a finger moves across a bent screen its path is three-dimensional. Moreover, the shortest distance between locations on the screen is not necessarily along the surface of the screen. We therefore decided to measure the three-dimensional movement of the fingers, not just their movement across the surface of the display. For this reason, we decided to use a Vicon 3D motion capture system [5] to measure finger movement as well as movements by the flexible display.

Not a Reciprocal Tapping Task

We specifically did not design our pointing task in the second study to be a Fitts' Law reciprocal tapping task, for good reason: such tasks feature targets between *two* locations on a screen and the outcome is a Fitts' Law model of the throughput of the interaction, across the entire amplitude of the display [7]. One reason to use point targets was our need to determine the speed and accuracy with which users could point at any *one* location on the display. A second reason was the low resolution of the Lumalive display, which did not allow for a wide variety of target widths. We therefore designed a task in which users were asked to point at single point targets distributed across the entire flexible display surface. As our second task, we included a dragging operation. This provided us with a second elementary UI action that related performance to structural integrity of the display [7]. To be able to precisely tie performance in the dragging task to the underlying 25 target areas on the display, we again purposefully did not vary the width in this task, but we did vary the amplitude with two target lengths: one at the full width of the display, and one at half the width.

Because of the 3D nature and potential curvature of the display, we observed that users often rested their pointing finger in mid-air, away from the display, between movements. To increase real-world validity of our experiment, and because it is non-trivial to define a specific 3D starting location in mid-air in front of the screen that is similar between holding gestures, we allowed users to choose their starting location freely. We then corrected for 3D distance of the path to target after the fact by calculating Fitts' Law's Index of Performance (IP) [7] per target location, allowing us to isolate time/accuracy tradeoffs for each location. Note that we would have had to correct for various distances to target even if we had defined a specific 2D starting location on the surface of the screen, as this was *not* a Fitts' Law reciprocal tapping task.

STUDY 2: METHODS & APPARATUS

For our experimental apparatus, we used an 8.5"*x*8.5" Lumalive flexible display consisting of 196 LEDs woven into a 14*x*14 pixel grid on a flexible plastic substrate. This substrate is normally sewn into a fabric pillow designed to be worn on the body. We modified the display to be more paper-like by removing it from its pillow, then covering it with a layer of thick 110 *g* paper, which also acted as a diffuser (see Fig. 4). The images shown on the Lumalive display were controlled via a remote control attached to an Arduino Mega microcontroller. Since this solution was not fully wireless, we designed a simple pulley apparatus that allowed the display as well as its battery to be balanced off its cable with a counterbalancing weight of 510 *g*. This allowed subjects to move the display freely in threespace without producing significant forces on the display surface.

Tracking

We tracked the hands and the movement of the display using a *Vicon MX 4* motion capture system [5]. Markers were attached to the four corners of the display, with a fifth marker on the cable to distinguish orientation. The hand was tracked by 2 markers on a wristband, with 1 marker on a finger cap (see Fig. 4). The communication between the Vicon, Arduino, and the storage of all the data was

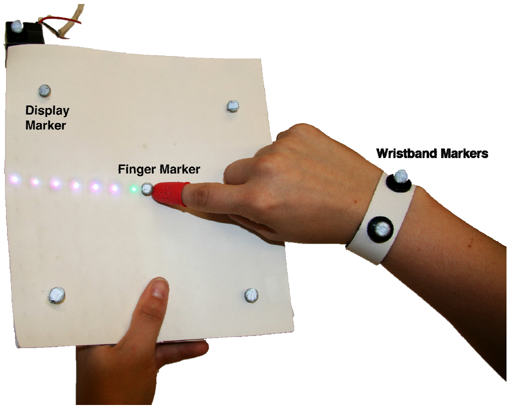


Figure 4. Flexible display with paper coating and 5 markers; wrist-band with 2 markers, finger cap with 1 marker.

managed in software. We modeled the shape of the paper by calculating Bezier curves between the four points on the display. A touch was registered whenever the marker on the tip of the finger was within 5 *mm* from the display surface. This meant the Vicon simulated a perfect capacitive touch surface that required no pressure to register a touch, with no crosstalk between holds and touches.

Tasks, Measurements and Procedure

For each task, we instructed participants to hold the display in each of the four holds obtained during the first study (see Figure 2).

Pointing Task

For the pointing task, we then asked participants to point at one of 25 randomly illuminated LEDs on the display, corresponding to the center of the 25 squares in Fig 3, as fast as possible without trading off accuracy. Each target was repeated 3 times. We trained users until their performance leveled off below 10% improvement in movement time (*MT*). Between trials, we asked participants to choose a position above the display, and hold their finger steady. We started *MT* measurements when users moved their finger more than 25 *mm* in threespace after presentation of the target on the display. We ended measurements when users were both within 5 *mm* of the display surface, taking into account its curvature, *and* within a two-dimensional radius of 7.5 *mm* from the target pixel. Trials where users were within 5 *mm* of the surface but outside the radius of the target area were flagged as error cases and discarded. Note that the mean error of Vicon measurements was below 3 *mm*.

Dragging Task

For the dragging task, because of the limited interactivity of the Lumalive, we asked participants to trace lines of illuminated LEDs on the display: a grid of 5 vertical and 5 horizontal lines of 19.5 *cm* evenly distributed across the entire screen, in each direction, and a plus formation of 2 vertical and 2 horizontal lines of 9 *cm* from each edge of the display to its center, and back. Each line was repeated 3 times, with a random order of presentation of lines. Training and instruction was similar to that in the pointing task. This dragging task was a compound task, in which the first component was a pointing task to acquire the beginning of the target, and the second part the actual dragging to the second target across the surface of the display. Participants were provided with an auditory stimulus after reaching the first target, and visual feedback upon reaching the second target. Since the first part was identical to pointing, we only analyzed the second part of this task. Measurement of *MT* started when users moved their finger more than 1 *mm* from the first target (after having successfully acquired that target). We ended measurement when users were within a two-dimensional radius of 7.5 *mm* from the target pixel. Trials where users moved their finger further than 5 *mm* from the display surface, while outside the radius of the target area, or stopped for longer than 80 *ms* before reaching the target, were flagged as error cases and discarded.

Experiment Design and Participants

We used 15 participants (mean age: 25.1; 9 males, 6 females). Participants were paid $10 for their participation. All participants in our study were right-handed.

For the pointing task, we used a fully factorial 4*x*25*x*3 within-subjects repeated measures design with two factors: hold (4 levels: *Vertical Center; Bottom Corner; Bottom Center* and *Bi-manual*) and location (25 levels, locations evenly distributed across the Lumalive display), and 3 trials per location. Order of presentation of holds was counterbalanced using a Latin square design.

For the dragging task, we used a within-subjects repeated measures design with three factors: hold (3 levels: *Vertical Center; Bottom Corner* and *Bottom Center*), amplitude (2 levels: 19.5 cm and 9 cm) and location (14 levels, evenly distributed across the display), with 3 trials per location. All conditions were counterbalanced for order using a Latin square design. Data for *Vertical Center* holds was discarded for 1 participant due to a system malfunction. The *Bi-manual* hold was not replicated in the dragging task because it approximates a one-handed *Vertical Center* hold.

For both tasks, we aggregated results for single locations into 3 levels pertaining to the structural areas from the first study (see Fig. 3): *grip* zone; *rigid* zone; and *flexible* zone, rendering a 4*x*3*x*3 fully factorial design for our pointing task and a 3*x*3*x*3 fully factorial design for our dragging task.

Analysis: Index of Performance

Although our experiment did not involve a classic Fitts' Law task, to calculate performance for each of the 25 target areas on the Lumalive display independently of the distance of the finger to the target, we treated each trial as having a Fitts' Law target with a certain bandwidth using the following formula:

$$(1) \qquad MT = a + b\log(A/W + 1) \qquad [7]$$

Hold	Vertical Center	Bottom Corner	Bottom Center	Bi-manual
Total excl.	9.7	8.9	9.1	6.3
Grip Zone	(.76)	(.60)	(.49)	(.30)
Error *(s.e.)*	2%	1%	3%	3%
Grip Zone	7.2	5.5	5.6	5.2
IP *(s.e.)*	*(.84)*	*(.58)*	*(.76)*	*(.35)*
Rigid Zone	10.1	9.4	9.9	6.5
IP *(s.e.)*	*(.76)*	*(.68)*	*(.54)*	*(.32)*
Flex Zone	9.3	8.3	8.3	6.1
IP *(s.e.)*	*(.80)*	*(.57)*	*(.50)*	*(.30)*

Table 1. Pointing Task: Mean IP and Error Rates for each of three structural zones for each of four holds.

The log component of this equation is called the Index of Difficulty (ID), while the a in this equation constitutes response time (RT) [7]. For the pointing task, each of the 25 target areas had a variable distance (A), freely determined by the participant, and a fixed target size (W) of 1.5 *cm*, the distance between pixels on the Lumalive display. We calculated b by dividing movement time (which excluded RT or a after accounting for display latency) by the ID for each trial. Note that in this calculation, only the movement time and the target distance (A) varied. We then calculated the Index of Performance (IP) for each of the 25 target areas by taking the reciprocal of b. While we only used this analysis procedure to correct our measurement for any differences in distance between conditions, conveniently, this produced a true measure of performance for each of the 25 target areas.

Assignment to Structural Areas

As per the heat maps obtained during Study 1, for each hold, we then assigned each of the 25 target areas to one of three structural zones within the hold: grip (dotted/red), rigid (hatched/green) or flexible (black). This process is illustrated in Figure 3. For pointing, per hold, we then averaged the IP value for the dotted/red squares to obtain the IP of the grip zone, and the IP of the hatched/green squares to obtain the IP of the rigid zone. The average of the remaining black areas constituted the IP for the flexible zone. We used a similar way of relating structural zones to dragging performance. First, we calculated the IP per participant for each of the 28 (2 sizes; 14 locations) dragging stimuli by dividing MT by ID of the task. We calculated ID using line length (19.5 *cm* or 9 *cm*) as the amplitude and 1.5 *cm* as the width. We then assigned each dragging stimulus to the subset of 25 areas on the display that were crossed. Our final data set consisted of 25 areas, with as a value the average IP taken over all dragging stimuli that crossed that location. These 25 areas were then mapped to the same 3 structural areas: grip, rigid and flex zones as per the above.

Questionnaire

After each trial, participants were given a questionnaire that asked about their enjoyment and efficiency ratings using positive statements, with agreement measured on a 5-point Likert scale (1 Strongly Disagree – 5 Strongly Agree). To reduce the time taken to answer questions, we used a larger grid of 9 areas on the display. Answers were mapped to the underlying 25 target areas and related to the same 3 structural areas: grip, rigid and flex zones, as per the above.

STUDY 2: RESULTS

We tested overall differences between conditions using a repeated measures Analysis of Variance ($p<.05$). Where pairwise comparisons were conducted, we used Bonferroni corrected posthoc t-tests ($p<.05$, one-tailed).

Pointing Task

Table 1 shows the total mean IP and error rates for each of the four different holds in the pointing task, grip zone data excluded. Overall differences in performance were significant between holds ($F(3, 42)=14.3$, $p<0.001$) as well as structural zone ($F(1,14)=27.8$, $p<0.001$). There were significant interaction effects between holds and structural areas ($F(3, 42)=2.9$, $p<0.05$). Pairwise comparisons show the *Bi-manual* hold to be the only significant outlier compared to all other hold conditions (Bonferroni, $p<.01$). Error rates were within 4%, with no significant differences between holds ($F(3,42)=2.3$, n.s.). Table 1 also shows the mean IP per hold for each of the three structural zones in the Lumalive display: the grip zone, rigid zone, and flexible zone. Differences in IP were significant between structural zones for all holds: *Vertical Center* ($F(2,28)= 6.4$, $p<0.01$); *Bottom Corner* ($F(2,28)= 37.5$, $p<0.001$); *Bottom Center* ($F(2,28)= 19.2$, $p<0.01$) and *Bi-manual* ($F(2,28)= 16.7$, $p<0.001$). Pairwise comparisons show structural zones to be significantly different from one another for all holds (Bonferroni, $p<0.05$).

Dragging Task

Table 2 shows the total mean IP and error rates for each of the three different holds in the dragging task, grip zone data excluded. For the dragging task, overall differences in performance were significant between structural zones ($F(2,28)=29.8$, $p<0.01$) but not between holds ($F(2, 28)=2.6$, n.s.) We found a significant interaction between holds and structural area ($F(4, 28)=7.4$, $p<0.01$). Error rates were again well within 4%, with no significant differences between holds ($F(2,28)=.55$, n.s.). Table 2 also shows mean IP and std. error per hold for each of the three structural zones of the display in the dragging task: grip zone, rigid zone, and flexible zone. Differences in IP were significant between structural zones for two out of three holds: *Vertical Center* ($F(2,26)= 6.0$, $p<0.01$) and *Bottom Center* ($F(2,28)= 4.3$, $p<0.05$). Pairwise comparisons showed these differences to lie between the rigid and flexible zones for both holds (Bonferroni, $p<0.05$). Differences between structural zones were not significant for the *Bottom Corner* hold ($F(2,28)= 2.4$, n.s).

Questionnaire and Participant Comments

When analyzed by structural zone, respondents considered the rigid zone of the display significantly more efficient for pointing than the flexible zone for the *Bottom Corner* (77% vs. 69% $Z=2.14$, $p<0.05$), *Bottom Center* (71% vs. 50% positive answers, $Z=1.72$, $p<0.05$) and *Bi-manual* (86% vs. 64%, $Z=1.75$, $p<0.05$) holds. When analyzed by structural

Hold	Vertical Center	Bottom Corner	Bottom Center
Total excl. Grip	5.9	5.5	5.8
Zone	*(.57)*	*(.50)*	*(.53)*
Error *(s.e.)*	2.9%	2.7%	2.4%
Grip Zone	6.3	5.9	6.1
IP *(s.e.)*	*(.53)*	*(.49)*	*(.65)*
Rigid	6.4	5.6	6.2
Zone IP *(s.e.)*	*(.67)*	*(.52)*	*(.49)*
Flex Zone	5.3	5.5	5.5
IP *(s.e.)*	*(.48)*	*(.48)*	*(.57)*

Table 2. Dragging Task: Mean IP and Error Rates for each of three structural zones for each of three holds.

zone, respondents considered the rigid zone of the display significantly more enjoyable during pointing than the flexible zone for the *Bi-manual* hold only (86% vs. 57% positive answers, Z=2.27, p<0.05). Results on this question were not significant for other holds. When analyzed by structural zone, respondents considered the rigid zone of the display significantly more enjoyable for dragging than the flexible zone for the *Bottom Center* (87% vs. 73%, Z=1.73, p<0.05) and *Bi-manual* (86% vs. 57%, Z=2.09, p<0.05) holds only. As for comments, in the pointing task, many participants commented the target was difficult to see *"when it was underneath my thumb"*. Participants in the dragging task indicated *"It was awkward when a line passed under my thumb"*. Sometimes, *"the view of a target was blocked by my right hand, while waiting for the next target"*. One participant commented that *"the further from the hold, the harder it was to touch"*. Many participants commented that they did not enjoy the *Bi-manual* hold because they had to switch hand position during the task.

STUDY 2: DISCUSSION

Results were largely in line with expectations. When pointing, the flexibility of the display surface material negatively impacts performance. However, when provided with an optimal touch sensitive surface that does not require a force to register touch, users were able to produce a sufficient normal force in the surface of the display for pointing and dragging operations, through structural folds. While the type of hold did affect the distribution of the structural forces in the display, with the exception of the *Bi-manual* hold, different holds produced similar performance. We surmise this was because of the way we selected holds from our first study: they were the most frequently deployed holds, presumably because they were the most useful. However, with the exception of the Bi-manual hold, holding preferences from the first study did not translate into significant performance differences in our second study. Instead, performance differences were due to differences in rigidity between structural zones *within* holds. This is true more so for pointing then for dragging operations, as the direction of the movement in relation to the fold lines in the display appeared relevant, as will be discussed in more detail below.

Pointing Task

For the pointing task, the only hold that negatively impacted performance was the *Bi-manual* hold. This was due to the fact that this was the only hold that required users to reposition their hand. A compounding issue may have been that this was also the only gesture in which the structural integrity of the display surface changed while pointing. Our main finding, however, is that the structural forces in a flexible display affect the Index of Performance of pointing operations. This meant that the measurements of rigid vs. flexible structural zones in a flexible display from our first study were successfully translated to our second study. We were able to predict, using data obtained with a Touchco pressure-sensitive flexible multi-touch device, which areas are affected by folds that increase rigidity, or structural integrity, of the display. We were able to show how zones with higher rigidity, on average over all holds, yielded a 12% higher Index of Performance over flexible zones, in pointing tasks. Results show users were able to radiate normal forces throughout the display through holds at the bezel. Grip zone, the area where the display was held, did have a significant effect on performance, for two reasons. Firstly, when the target was inside the grip zone it was, in some cases, obscured by the thumb. This *"fat thumb"* problem was confirmed by participant comments: we could not, and did not want to control *exactly* how users would hold the display over time, despite instructing participants on the way in which they were to hold the display. Secondly, the grip zone interfered, in some cases, with pointing activity. Observations showed users resolving this by moving the grip slightly, which may have negatively affected performance as well. We isolated this problem by excluding data from grip zones when comparing overall performance. Overall, holds did not have a significant effect on error rates, which were well within the margins typically reported in pointing experiments.

Dragging Task

Our results for the dragging task mimicked those for pointing, but with lower IP values, which is consistent with the literature [7]. Again, areas with higher rigidity produced approximately 12% higher performance in the dragging task than areas that were more flexible, with the actual hold not having a significant effect. There was, however, a significant interaction effect between hold and structural area: this was likely due to the *Bottom Corner* hold, which produced results in this task that appeared different from the other holds. The likely reason for this was that the structural forces in this hold ran diagonally across the screen, whereas the target lines were presented either vertically or horizontally. This meant that many of the horizontal and vertical dragging targets obtained performance gains while crossing this area, benefits that were then carried over across the entire drag zone during analysis. This likely removed differences between structural zones in this condition. This also means that orientation of the dragging stimulus may have an effect on performance. It is likely that, for dragging tasks that are diagonally laid out across a flexible display, the other holds would not have yielded a significant difference. This means that dragging performance is likely similarly affected by the rigidity of a structural zone as pointing performance, in that performance is boosted whenever the finger hits an area of high rigidity. There is, however, no easy way to analyze this effect, as dragging tasks typically cross both rigid and flexible zones. We see proper analysis of effects of directionality on dragging performance in flexible displays as a future direction of this work, but conclude that, at least in our task situation and with our horizontal and vertical target sets, structural integrity of the display surface mattered. Again, holds did not have a significant effect on error rates, which were well within the margins typically reported. As opposed to the pointing task, however, the grip zone had no discernable effect on the dragging task, with similar performance between grip and rigid zones of the display. This was likely because visibility of targets was not affected by grip zone in this task: targets were a line rather than a single pixel. Furthermore, the grip zone is one of the most rigid areas in the display, and would be expected to have the highest performance of all areas as long as there is no *"fat thumb"* problem.

Design Recommendations

Our study shows that there are issues to be resolved before flexible touch technology becomes viable as a source of input for flexible displays. E.g., Touchco is pressure-sensitive, which is problematic for flexible areas of the display. As for the capacitive Displax film, the presence of a thumb in the grip zone interfered with sensing in the rest of the surface. Our study does provide guidance on design. Firstly, while flexibility of the display negatively impacts performance in pointing and dragging tasks, users are capable of achieving good levels of performance. This is due to the structural support provided by holds that curve the display. Designs for flexible display hardware need to accommodate for such structural folds. Secondly, we recommend that, like rigid tablet PCs, flexible touch screens use a bezel to avoid *"fat thumb"* problems in grip zones. This could take the form of a paper-style margin. Thirdly, interactive graphics in flexible parts of the screen could be enlarged to allow for bigger targets, or could move to rigid areas of the display, depending on the kind of hold.

Limitations

Our study was limited to right-handed participants. We believe results would be mirrored for left-handed individuals. Results pertain to displays with the rigidity of Lumalive. However, given measurements from our 1st study yielded significant performance differences in our 2nd study, we believe observations would translate to paper and other more flexible displays. Display and hand size may impact results, because of its impact on structural forces. Results may have been different had we used a flexible touch screen instead of a Vicon. Finally, direction of dragging may have limited generalization of our 2nd task: for omnidirectional drags, effects on IP may be more evenly spread across structural areas of the display.

CONCLUSIONS

We presented a study of the effects of structural holds and rigidity of a flexible display on touch pointing and dragging performance. We collected commonly used holds with a mockup paper display, along with data on forces these holds generated within the display surface. We analyzed this data to produce 3 force zones for each of the four most frequently observed holds: the *grip* zone, *rigid* zone, and the *flexible* zone. Our empirical evaluation compared the efficiency of pointing and dragging operations between holds, and between structural zones within holds, using a flexible Lumalive display. Results suggest that the force characteristics of folds in a flexible display matter. Performance in pointing and dragging tasks is, on average, 12% better in rigid than in flexible parts of the display.

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