Understanding Touch Selection Accuracy on Flat and Hemispherical Deformable Surfaces

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Abstract

Touch technology is rapidly evolving, and soon deformable, movable and malleable touch interfaces may be part of everyday computing. While there has been a lot of work on understanding touch interactions on flat surfaces, as well as recent work about pointing on curved surfaces, little is known about how surface deformation affects touch interactions. This paper presents the study of how different features of deformable surfaces affect touch selection accuracy, both in terms of position and control of the deformation distance, which refers to the distance traveled by the finger when deforming the surface. We conducted three separate user studies, investigating how touch interactions on a deformable surface are affected not only by the compliant force feedback generated by the elastic surface, but also by the use of *visual feedback*, the use of a *tactile delimiter* to indicate the maximum deformation distance, and the use of *hemispherical surface shape*. The results indicate that, when provided with visual feedback, users can achieve sub-millimeter precision for deformation distance. In addition, without visual feedback, users tend to overestimate deformation distance especially in conditions that require less deformation and therefore provide less surface tension. While the use of a tactile delimiter to indicate maximum deformation improves the distance estimation accuracy, it does not eliminate overestimation. Finally, the shape of the surface also affects touch selection accuracy for both touch position and deformation distance.

Keywords: Touch; flexible displays; pointing.

Index Terms: H.5.2. Information interfaces and presentation (e.g., HCI): User Interfaces: Input Devices and Strategies, Interaction Styles.

1 Introduction

With the dissemination of tablets and smartphones, touch-based interaction is already an integral part of everyday computing. Given such wide adoption of touch and multi-touch technology, much research has gone into extending the touch interaction vocabulary by adding additional input dimensions to touch sensing. For example, numerous projects demonstrated the benefits of non-flat touch surfaces [2], touch pressure [15], tracking of fingers and gestures above the surface [9], and the use of deformable surfaces [19]. However, while there is a deep understanding of touch interactions on typical flat rigid surfaces [10], and some understanding of the effects of curvature [16], knowledge of the impact that surface deformation has on touch interaction is still limited.

In this paper, we investigate how touch interactions are affected when the surface is non-rigid and when surface deformation is used as an additional dimension in touch input. While we are not the first to propose adding surface deformations as an additional input dimension to touch input [3, 13, 19, 22], to our knowledge, this is a first systematic evaluation of the effects of surface deformation on touch performance.

The main contribution of this paper is in gathering data about touch selection tasks on deformable touch surfaces and in providing insights that can be used in the design of such interfaces in the future. There are many aspects about a deformable touch surface that merit deeper investigation. For example, what kind of feedback is necessary for users to achieve high levels of accuracy? Is compliant force feedback enough? Can user's estimation of deformation distance be improved by using a rigid barrier at the pre-set maximum surface deformation (we refer to this feedback as a tactile delimiter)? When is it necessary to have a visual indication of how far your finger is pushed into the deformable surface (visual feedback)? How does the surface shape affect precision in pointing? How does multi-touch function on a deformable surface? Given such a rich design space, a complete analysis of this space is beyond the scope of this paper.

Instead, in order to answer some of these questions, we built several prototype devices and applications, and performed three user studies to evaluate touch selection accuracy on deformable touch surfaces focusing on three characteristics: (1) the impact of visual feedback, (2) the impact of tactile delimiters, and (3) the impact of a deformable surface shape (hemisphere vs. flat shape). Figure 1 illustrates the different measures we investigated.

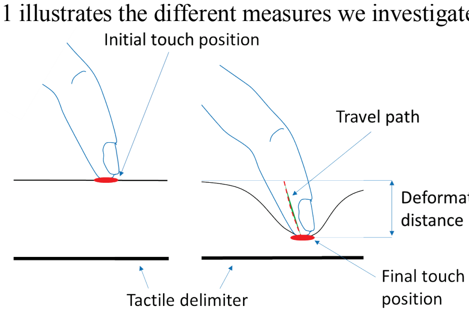

Figure 1: Different measures investigated in our experiments.

The main findings presented in this paper can be summarized as:

- Users can perform touch selection tasks on deformable surfaces with sub-millimeter accuracy when provided with some form of visual feedback;
- Users overestimate deformation distance when no visual feedback is provided, meaning they deform the surface more than they think they do;
- The use of the rigid tactile delimiter improves deformation distance estimates, but does not eliminate overestimation;

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- The shape of a deformable surface affects both position and travel path in touch selection accuracy.

2 Related Work

As mentioned before, much research has gone into extending touch interaction capabilities. For example, non-flat shaped objects such as a sphere [2] allow users to interact with applications that can be better mapped to the surface approximating the object. In the case of a sphere, for example, the surface of the Earth can be directly mapped to the display to provide more intuitive interactions. BendDesk [23] combines vertical and horizontal touch screens with a curved, touch-enabled area. Another example is the OmniTouch [6], which allows users to transform any surface within their reach into a touch-screen. While such examples extend touch interactions onto non-flat surfaces, the interactions themselves remain completely in two dimensions.

Another solution for this problem is provided by pressure-sensitive touch devices, such as the UnMousePad [15]. With it, users can use force on the touch surface as an extra dimension, and new types of gestures and interactions can be used. This concept is presented by Ramos et al. [14] using pressure with a stylus to define new gestures. Another alternative is to use tangible devices above the surface [8]. The problem with the pressure sensing approach, however, is that while the depth dimension can be provided, it flattens out 3D interaction, and important cues such as Z-position in space are only provided by force. This could make it difficult, for example, for users to estimate the amount of force necessary to travel a determined amount along the depth axis [1, 18].

One approach to address these problems is to provide different interactions above the touch surface. For example, Spindler et al. [17] provide a position tracked surface that is used as a lens to visualize different parts of a 3D dataset. This approach is similar to the one implemented in our volume visualization demo. The continuous interaction space [12] integrates touch and gestures in the space above the surface. LightSpace [24] extends this idea further by allowing users to interact between displays. Although this approach provides distance as a new dimension, it forces the user to perform interactions mid-air, without force-feedback. With this, precision issues may arise for both position and distance from surface.

Shape changing devices can also be used to augment normal touch interfaces. For example, Harrison and Hudson [7] used deformability to provide tactile feedback for buttons on a touch screen. More recently, Follmer et al. [4] presented the concept of Jamming User Interfaces, in which a malleable device can be jammed into different shapes and be used as input devices. Leithinger et al. [11] showed the use of gestures to control 2.5D display.

Finally, surfaces that deform as the user applies force to them can be used to overcome these limitations. For example, Peschke et al. [13] showed how a Microsoft Kinect can be used to track deformation of large surface areas and demonstrated an application that uses deformation to interact with virtual spheres. Another example was presented by Watanabe et al. [22], which tracked deformation of an elastic vertical surface using fiducial markers projected onto the surface with an IR projector and a camera with an IR-pass filter. A few applications were demonstrated, such as 3D surface sculpting and volume slicing. We implemented these two applications using our prototypes. The Khronos Projector [3] is perhaps the most similar in terms of implementation of hardware. A camera with an IR illumination ring is used to detect variations in light reflected from a malleable surface to track deformation. The setup is used in an application that gives temporal control over video data based on the deformation of the surface. Finally, Stevenson et al. [19] presented an inflatable hemispherical display that supported multi-touch, and used infrared illumination to determine surface deformation. The main application for this was Google Earth, in which the surface inflates/deflates to match the Earth's curvature at different levels of zoom. Our hemisphere prototype is different in that it has constant air pressure and shape when not touched, and employs a hard internal wall to indicate the end of travel is achieved (the tactile delimiter). These design decisions were related to one of our goals: to evaluate how much shape affects our perception of deformation distance. This is also related to the main difference between previous work in deformable surfaces and our work. Our focus is not on the system or the applications that could use devices like these, but understanding how deformation affects touch selection tasks on touch surfaces.

While touch selection tasks on regular touch surfaces are fairly well studied [10, 21], there is still little to no understanding of how the extensions presented here affect these tasks. Roudaut et al. [16] presented an evaluation of touch on curved surfaces that explored different types of curvature (convex and concave) and different amounts of curvature, and evaluated how well users could perform touch selection tasks on them. The results were used to provide recommendations to interaction designers, such as a method for calculating the minimum size of a button when it is presented in specific conditions of curvature and position. Our focus, on the other hand, is on deformable surfaces and how visual feedback, the use of a tactile delimiter, and the shape affect touch performance.

3 Deformable Surface Prototypes

To enable us to study how deformation of the surface affects the touch pointing task, we designed a series of custom hardware prototypes and custom touch tracking software. In particular, we needed a platform which would let us experiment with both flat and curved deformable surfaces as well as offer an easy way to provide or remove the tactile delimiter at varying depths to denote maximum deformation to the user.

Our current test hardware (Figure 2) is large and not easily adaptable for real-world products; however, we designed it specifically as a test framework for our experiments to enable us to understand human touch behaviour when interacting with deformable surfaces.

3.1 Hardware

We designed and built two deformable surfaces: flat and hemispherical (Figure 2). Both prototypes consist of a compliant top surface (latex + Spandex combination), a tactile delimiter, and a wide angle camera and projector unit underneath to track touch locations and deformation amounts. Our flat prototype also has an adjustable height mechanism for the tactile delimiter,

For the deformable surface, we chose latex because it provides elasticity and compliant force feedback. However, we found that latex alone causes specular reflections when stretched, which in turn generated problems for our IR camera-based tracking of fingertips. Our solution was to glue a layer of Spandex stretchable fabric on the inside of the deformable surface (facing the camera) to create a diffuse reflecting surface for tracking.

For touch sensing, we tested a wide range of setups, including depth sensing cameras; however, we settled on using a configuration which combines an IR camera and a projector which share the same optical path through a wide angle secondary lens (Figure 3). We mounted a custom IR light emitter mounted around a wide angle lens, and we use the amount of light reflected by the user's fingers to compute the distance to the surface (for validation see Section 3.1.1). The reason for using a wide angle lens was to minimize the distance between the surface and the IR illumination source, which in turn gives us a wider dynamic range and greatly improved accuracy for calculating deformation distance. This setup is similar to the Sphere project by Benko et al. [2]. The projector allowed us to use our prototypes as output devices as well.

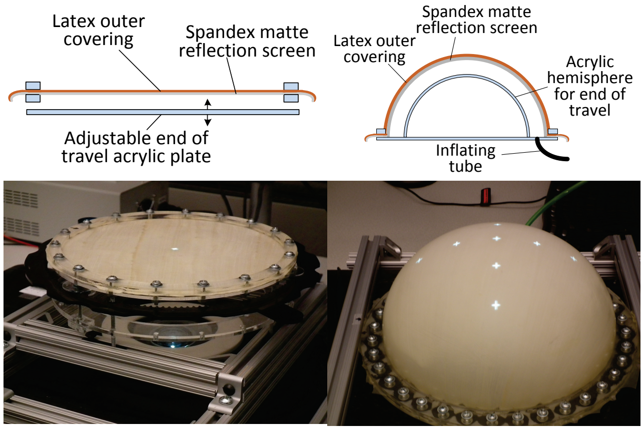

Figure 2: The two prototypes used in the studies: (left) the flat surface design, and (right) the inflatable hemisphere.

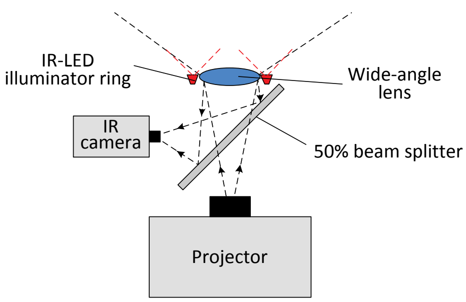

Figure 3: Setup used for projection and tracking.

With both the setup and materials decided, we designed and built the final set of prototypes (seen in Figure 2). On the other hand, the new prototypes, both flat and hemispherical, provided a tactile delimiter and required a similar amount of force to reach the same amount of deformation. Finally, while the hemispherical prototype provided a delimiter by using a fixed acrylic dome beneath the deformable surface, the flat prototype featured a height adjustable/removable acrylic plate. All prototypes could also be used as an output device using the optically aligned projector.

3.1.1 Prototype Validation

To ensure our prototypes provided us with enough accuracy, we built a device to simulate touch with a constrained travel and measurable path (Figure 4). For every target on the flat and hemispherical surface we repeated the same task of moving the device away from the surface and then pushing it until it touched the tactile delimiter located at 30mm a total of 50 times.

For the hemisphere, the device was also angled to test different inclinations on the hemisphere and to move along the hemisphere surface normal. This test was done iteratively to adjust the tracking algorithm values. For 0° inclination, our device average measurement was 29.89mm for 30mm deformation on both flat and hemispherical prototypes, with a confidence interval (at 95%) of 0.22mm. For 22.5° inclination on the hemisphere, the final measured deformation distance was 29.57mm, with a confidence interval (at 95%) of 0.14mm. Finally, for 45° inclination on the hemisphere, the final measured deformation distance was 30.03mm, with a confidence interval (at 95%) of 0.22mm.

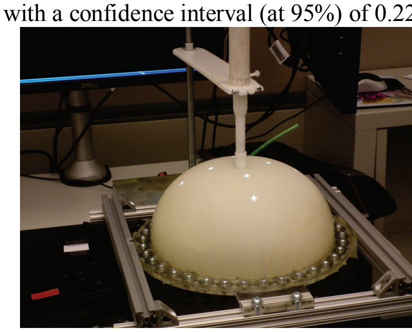

Figure 4: The device used to measure precision for deformation distance and position of our prototypes. Note: the device was angled to test different inclinations on the hemisphere to move along the surface normal.

3.1.2 Force Response Function

To further characterize our devices, we used the same validation apparatus to measure the necessary force to deformation function of the different prototypes. For both flat and hemispherical prototypes, we measured the amount of force necessary to deform the surface at the center of the device, starting from 0mm and measuring up to 30mm with a 5mm interval. We used a small precision weight-scale underneath the prototypes, measured the force and converted to Newtons (N). Figure 5 shows the different measurements and the linear regression used to find the force to deformation function for each prototype. Since vertical displacements in a horizontally configured rubber membrane adhere to Hooke's Law (i.e., linear force vs. displacement behavior) [5] we expected to find linear relationship between the force and displacement.

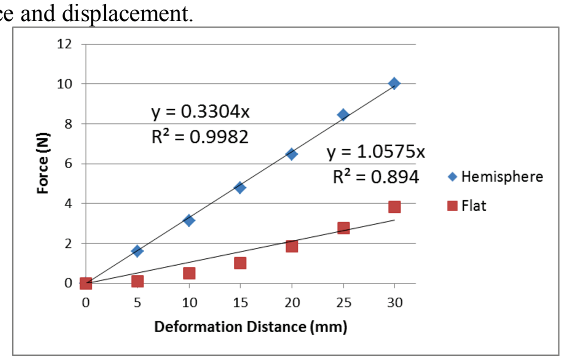

Figure 5: Measured force for different deformation distances.

While the measurements for the hemisphere prototype clearly show a linear response for deformation, the flat prototype seems to present an exponential response up to 10mm, and linear response after that. This is slightly different from what we expected, but we believe the reason for that is the very small amount of weight necessary to perform small deformations. Overall, since our measured results show near-linear response for both flat and hemisphere surface, we believe that our subsequent experimental results (Sections 4) can generalize well for any other linear or near-linear response deformable surfaces.

3.2 Software

The experimental software was written using OpenGL for rendering and a customized version of openFrameworks for tracking of both position and deformation. Tracking was performed in two parts: first, tracking of touch position (without considering deformation distance) was done with the blob detection and tracking techniques available in the library; next, illumination at the center of each detected blob was recorded and used to determine new thresholds to be used in the first part. Using the difference in illumination (the closer the surface was to the camera, the brighter it was) and the calibration process described in the previous section, we are able to determine deformation distance. Performing this process for each detected touch point increases accuracy and allows us to track deformation distance for multiple blobs precisely.

3.2.1 Demos

To test how well our system would fare in real world applications, we built two prototype applications: a terrain modeler, and a volume visualization tool (Figure 6).

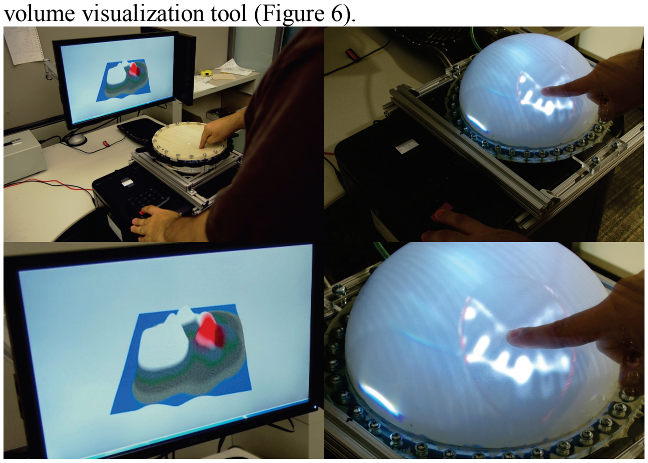

Figure 6: Two prototype applications developed to test and demonstrate how deformable surfaces can be used.

The terrain modeler allows users to manipulate a three-dimensional mesh, using our flat prototype as an input device and monitor as the output. The surface of the device is mapped to the mesh, and deformations on the surface affect the terrain. The volume visualization tool maps volumetric data, such as stacks of medical imaging, to the surface of the hemispherical prototype. Deforming the surface along the surface creates a lens-like visualization tool allowing users to navigate the volume by viewing the 2D image slice of the 3D data at the selected depth.

4 Evaluation of Touch Selection Performance

We conducted three experiments comparing the use of visual feedback, a tactile delimiter, and different shapes for deformable surfaces. Visual feedback allows us to evaluate how accurate users can be if provided with information about deformation distance. This can be the baseline for other studies, and shows the maximum performance. The use of a tactile delimiter relates to real world applications, in which users may have a limit in the deformation of the surface. It also shows the benefits of not only providing tactile feedback when the user touches the surface with no deformation, but providing information about what the maximum deformation is. Finally, the motivation for studying a different shape is to gather insights about how the initial shape of the surface affects the travel path, from the initial touch position to final touch position. We evaluated the task of selection with different positions and required deformation distance. Sections 4.1, 4.2, and 4.3 refer to the overall experimental design, and the following sections discuss design and results of each experiment.

4.1 Experimental Setup

In addition to the prototypes described in the previous section, our studies had a few other components that together composed the final setup. Participants sat in a chair in front of the device, at approximately the same height from the ground. This was done in order to guarantee that participants would see the targets from the same position. The enter key (painted red) of a numeric keyboard was used to start and end each trial. Participants used their left hand to press the key and their right hand to perform the task. A 30mm reference ruler was placed beside the prototype so that participants would know the size of the maximum required travel distance. The participant setup is illustrated in Figure 7.

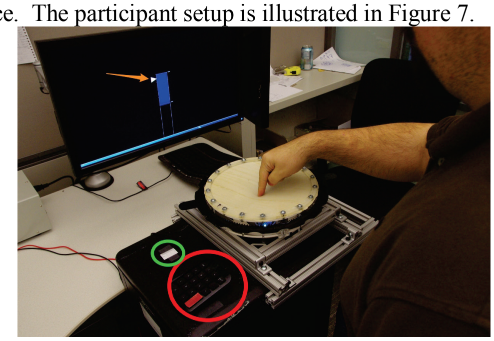

Figure 7: Participant point-of-view during the study: the circles indicate the numeric keyboard with the red key and the reference ruler (green); and the arrow shows the depth meter displayed on the vertical screen with a triangle marker denoting the required deformation distance for a given task.

Two vertical displays were used: one for the participant and one for the experimenter. In addition, the deformable surface was a projected display as described above. The target was displayed directly on the surface using the projection system and consisted of a white cross. The vertical display, directly in front of them, contained a virtual meter to illustrate deformation distance. A triangle marker was used to provide an indication of the required travel distance, and visual feedback provided with an animated blue bar. An additional display was used to provide information about the system, task and performance to the experimenter.

4.2 Participants

A total of 12 participants were recruited to perform the all three studies in one session, and they were compensated with a $10 coupon. Participants' ages ranged from 18 to 30 years old, with a median age of 20. Five participants were female. All participants were right-handed.

We used a factorial within-subject design with repeated measures across all three studies, and participants performed a total of 300 tasks, with 71 different conditions. The order of presentation of the different studies was counterbalanced.

4.3 Procedure

Upon arrival, participants were screened for right-handedness and proceeded to complete a background questionnaire. After that, they were shown the experimental setting and given initial instructions. All participants completed a total of 32 practice trials with different travel distances and visual feedback on the flat surface before starting the experiment. This was provided for all participants allowing them to experience the travel distances using visual feedback. After completing the initial tutorial, they were given a practice session on the current condition in which they had to practice all different travel distances in that condition.

Before starting the trials, participants were reminded that they should try to be as accurate as possible, perform the trials using their fingertips and not rest their palms on the device. This was done to minimize possible confounds such as using the device to stabilize their hands for more position accuracy. Additionally, before the start of each task, participants were asked to remove fingers from the touch surface so that they would always have to start touching and deforming the surface when starting a task. An error message would appear until there were no fingers detected.

The task procedure was always the same: first press the red key to start the task; then touch the target and match the travel distance indicated by the marker; and finally press the red key again to confirm.

At the end of each study session, participants rested for two minutes while the next study was setup. Then they moved on to the next study, following the same protocol until all three studies were completed. Finally, the participant filled out a post-experiment questionnaire, comparing all studies and rating the difficulty of performing the pointing task in each one of them.

4.4 Study 1 – Evaluation of Deformation Distance Accuracy with Visual Feedback

The overall goal of this study was to determine how accurate can participants be in deforming the surface with constant direction (vertically) and a certain distance if given visual feedback. This task gives us an upper bound on user's accuracy given precise visual feedback and the results serve as a baseline for the other studies.

The main hypothesis for this study was that users would be able to perform touch selection accurately with an interval of 2mm between required deformation distances (H1). This number is defined by Hong et al. [20] as an estimation of the human detection threshold for fingertip movement, and we expected visual feedback to help users achieve this threshold. We also expected distance to not affect the position precision for our task (H2).

4.4.1 Experimental Design

For study 1, there was only one independent variable: *Deformation Distance* (from 0mm to 30mm, every 2mm for a total of 16 different deformation distances). This study was performed using the *flat* prototype, and *visual feedback* as provided for all conditions. Targets were always in the center of the surface to ensure the same material resistance across all conditions (requiring ~3.8N to achieve maximum deformation). The order of presentation of the deformation distances was randomized. Each condition was repeated five times, giving a total of 80 trials.

4.4.2 Results

We first analyzed the measured deformation distance. A repeated measures ANOVA found a significant effect of measured deformation distance for the different required *Deformation Distances* ($F_{15,165}$=6481.5, p<0.001). Further analysis showed a high fit coefficient (R^2=0.99) of the mean measured deformation distance to the task deformation distance. This confirms our hypothesis H1 that visual feedback can help users surpass the human detection threshold for fingertip movement.

However, the measured deformation distance has a slight offset when the task deformation distance is small. To analyze this effect further, we calculated the difference between task deformation distance and measured deformation (deformation distance error). Again, a repeated measures ANOVA showed significant effects ($F_{15,165}$=4.518, p<0.001) for error in the measured deformation distance. The graph in Figure 8 shows that the less deformation a task required, the more participants overestimated it.

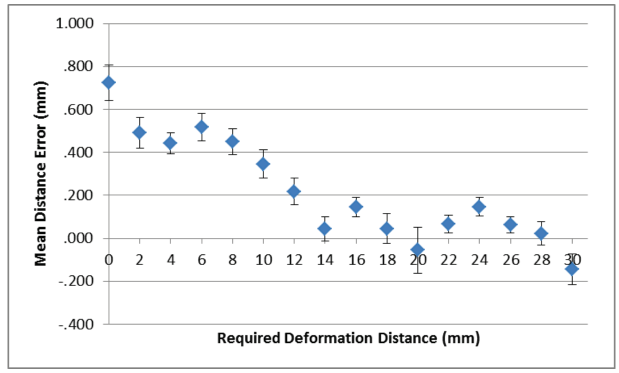

Figure 8: Mean deformation distance error. Error bars represent standard error.

Finally, we also analyzed data relative to the offset in position from the initial touch position to the final touch position. Surprisingly, the required *Deformation Distance* had a statistically significant effect on the offset distance (refuting H2). A factorial repeated measures ANOVA showed significant effects of *Deformation Distance* for the overall offset distance ($F_{15,165}$=13.549, p<0.001). Figure 9 shows the mean offset for every user with different required *Deformation Distances*. Participants tended to push the target to the left and back the more deformation distance was required by the task.

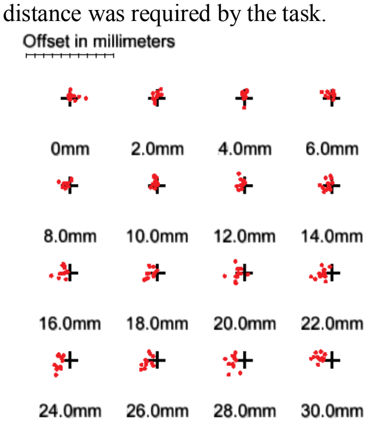

Figure 9: Offset error for each one of the required *Deformation Distances* in Study 1. Each point represents the mean offset error for one user.

4.5 Study 2 – Evaluation of Accuracy with Tactile Delimiter

The goal of this study was to find how effective is compliant passive force feedback alone for users to estimate deformation distance, and how much better would they get if a firm tactile delimiter was used to provide a reference point at the maximum distance. This evaluation was designed to give us insight into whether users can perform selection tasks at different deformation distances without visual feedback, and how many different distances they can effectively estimate.

The main hypothesis for this study was that users would be precise in estimating different deformation distances without visual feedback, but would not perform tasks accurately without the tactile delimiter (H3). For this reason, we chose to use five different distances, in a greater interval than in the previous study (7.5mm). Our secondary hypothesis for deformation distance was that the tactile delimiter at the maximum deformation distance would improve precision (H4). Third, we expected deformation distance and the use of a tactile delimiter to not affect the position precision for our task (H5).

4.5.1 Experimental Design

For study 2, there were two independent variables: *Deformation Distance* (0mm, 7.5mm, 15mm, 22.5mm, 30mm), and *Tactile Delimiter* (either with or without). This study was also performed using the *flat* prototype. *Visual Feedback* was not provided during these tests. Again, targets were always placed in the center to ensure the same lateral resistance. The order of presentation of *Deformation Distance* was counterbalanced, and *Travel Delimiter* randomized. Each condition was repeated four times, for a total of 40 trials.

4.5.2 Results

The first analysis for this study is about measured deformation distance. A factorial repeated measures ANOVA found a significant effect for the different required *Deformation Distances* ($F_{4,44}$=251.248, p<0.001), which means that users can estimate different distances based on surface deformation, and *Tactile Delimiter* ($F_{1,11}$=72.992, p<0.001), which means that the use of a tactile delimiter affects the estimated deformation distance. Further analysis shows that the interaction between *Deformation Distance* and *Tactile Delimiter* was significant ($F_{4,44}$=16.232, p<0.001). Figure 10 shows this interaction, in which the mean measured deformation distance is closer to that required by the task when tactile delimiter is used. These results confirm our hypotheses H3 and H4 that error is reduced when tactile delimiter is available.

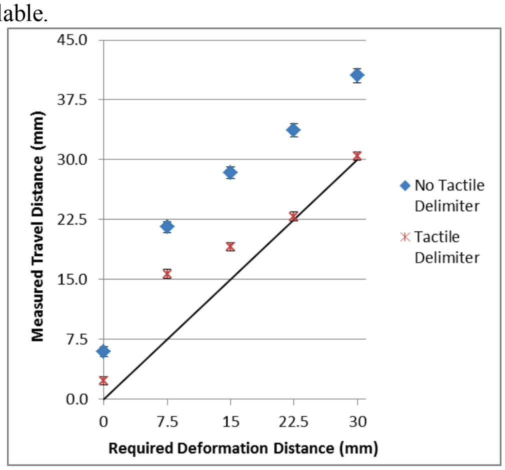

Figure 10: Mean deformation distance with and without tactile delimiter, and required deformation distance represented by the line. Error bars represent standard error.

Figure 10 also shows that participants had the tendency to overestimate the distance when they were required to deform short distances, similarly to Study 1. In this case, however, this effect is accentuated by the lack of visual feedback. A factorial repeated measures ANOVA found significant effects on deformation distance error for *Deformation Distance* ($F_{4,44}$=14.455, p<0.001), *Tactile Delimiter* ($F_{1,11}$=72.994, p<0.001), and their interaction ($F_{4,44}$=16.232, p<0.001).

The analysis of the position offset between initial and final touch positions showed that *Tactile Delimiter* did not affect the offset distance. On the other hand, like in Study 1, *Deformation Distance* showed a significant effect overall (both with and without the *Tactile Delimiter)* in the offset distance ($F_{4,44}$=23.86, p<0.001), which refutes H5. The interaction between the two variables was not significant. Figure 11 shows the mean offset distance for every user with each different *Deformation Distance*, with and without touch feedback. Following the same tendency presented in Study 1, participants pushed the target to the left and back the more deformation distance was required by the task.

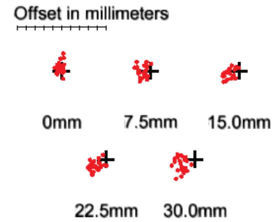

Figure 11 – Offset error for each one of the required *Deformation Distances* in Study 2. Each point represents the mean offset error for one user.

4.6 Study 3 – Evaluation of Accuracy with a Hemispherical Touch Surface

The main goal of this last study was to shed light on how user's performance differs on a different deformable shape. While many different shapes are possible, we chose to experiment on a hemispherical shape, since it allows us to control and evaluate surface curvature more precisely. This shape, in addition to having been previously explored in other touch performance experiments, has continuous and uniform curvature. By analyzing touch selection in different positions of the hemisphere, we are able to understand how the curvature affects travel and path precision. The position of the different points on the hemisphere is represented in Figure 12.

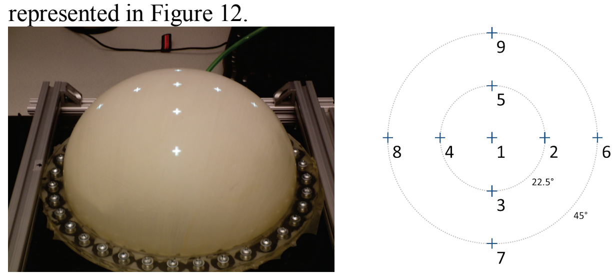

Figure 12: Different target positions on the surface of the sphere, with 3 latitudes (0°, 22.5°, 45°) and 4 longitudes (0°, 90°, 180°, 270°), for a total of 9 positions.

The hypotheses for this study were that: (H6) there would be a significant effect of position of the target on the hemisphere on path accuracy; and (H7) deformation distance accuracy would be influenced by the position of the target. These hypotheses can be related to the results presented in [16], which showed that different levels of curvature result in different amounts of error (e.g., convex surfaces result in more accuracy).

4.6.1 Experimental Design

For study 3, there were two independent variables: *Deformation Distance* (0mm, 7.5mm, 15mm, 22.5mm, 30mm), and *Target Position* (3 latitudes: 0°, 22.5°, 45°; 4 longitudes: 0°, 90°, 180°, 270°; total of 9 positions). We carefully chose the points on the hemisphere to keep the amount of force required to reach maximum deformation constant. This study was performed using the hemispherical prototype. The *Touch Delimiter* was provided for all conditions, and *Visual Feedback* was not. The order of presentation of both *Deformation Distance* and *Target Position* was randomized. Each condition was repeated four times, for a total of 180 trials.

4.6.2 Results

The analysis of measured deformation distance for this study takes into account both required *Deformation Distance* and *Target Position* on the hemisphere. A factorial repeated measures

ANOVA found a significant effect of measured deformation distance for the different required *Deformation Distances* ($F_{4,44}$=123.573, p<0.001), which means that users were able to estimate different distances for the different required *Deformation Distances*, and *Target Position* ($F_{8,88}$=15.923, p<0.001), which means that *Target Position* affected the estimation.

The analysis of the interaction between *Deformation Distance* and *Target Position* also shows significant effects ($F_{32,352}$=4.976, p<0.001). This means that the measured deformation distances for the different required *Deformation Distances* changed for each one of the different target positions. This confirms our hypothesis H7). This effect can be seen in Figure 13, which shows how the measured deformation distance compares to the required *Deformation Distances* for each one of different target positions.

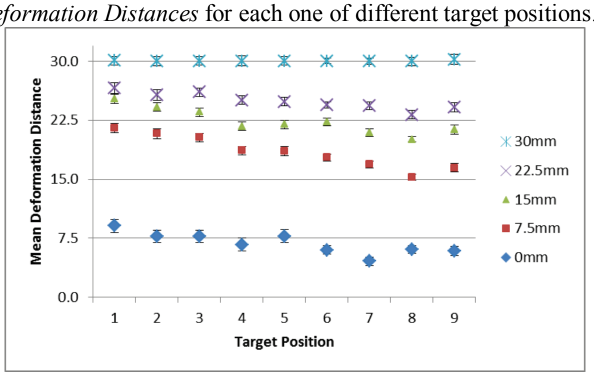

Figure 13: Mean deformation distance for different target positions on the sphere. Different shapes indicate different required deformation distances, and error bars represent standard error.

The analysis of the position offset between the initial and final touch positions showed that, overall, *Deformation Distance* did not have an effect on offset distance. On the other hand, as expected, *Target Position* had a significant effect on the offset distance ($F_{8,88}$=5.037, p<0.001), confirming our hypothesis H6. Figure 14 illustrates the mean offset distance for each user and different target positions, when the requested *Deformation Distance* was the maximum distance (30mm). As can be seen, the device shape affects the participant's ability to select targets differently than the flat shape.

4.7 User Preference

It is also interesting to look at subjective ratings the participants gave for the different studies and conditions. Participants rated the difficulty of the conditions in a scale from 1 (very hard) to 7 (very easy). We performed Wilcoxon Signed Rank tests on each of the questions. The conditions in which participants were provided with visual feedback (mdn=6) were rated significantly easier to perform than without visual feedback and without tactile delimiter (mdn=3, n=12, W=75, p<0.01) and with the hemispherical shape (mdn=3, n=12, W=76, p<0.01). The conditions that provided a tactile delimiter (mdn=6) were also considered significantly easier than without tactile delimiter (mdn=3, n=12, W=78, p<0.01) and with the hemispherical shape (mdn=3, n=12, W=78, p<0.01). No statistically significant differences were found in preference between visual feedback and the use of a tactile delimiter, and between shape and not using a tactile delimiter.

5 Discussion and Conclusions

The results for the visual feedback experiment show that participants were able to achieve sub-millimeter precision for travel when using it. If the application being designed requires a high level of accuracy from the user, some form of visual feedback is a clear requirement.

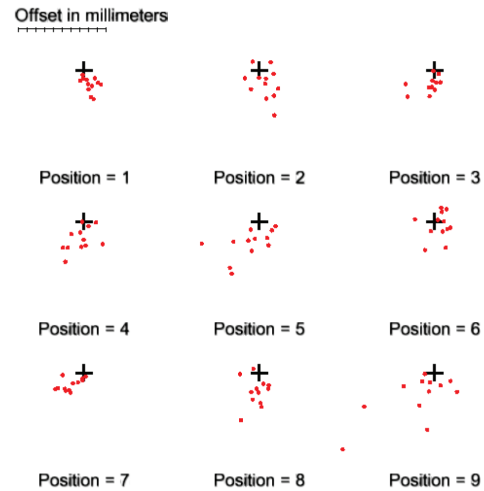

Figure 14: Offset error for each one of the different *Target Positions* in Study 3, with *Deformation Distance* constant at 30mm. Each point represents the mean offset error for one user.

Without visual feedback, participants are able to identify five different deformation distances within 30mm, and even though accuracy was low, meaning that they missed the target deformation distance, precision was high, meaning that the error was consistent. With this in mind, we think it is possible to use deformation as a new dimension for touch even if there is no visual feedback or a tactile delimiter, given that the system is calibrated to account for error.

On the other hand, the tactile delimiter proved to be an important asset in improving on the accuracy issue even when the required deformation distance is far from it, since there was a significant difference in the amount of error that was seen when using the delimiter. Based on our results, we can say that without a tactile delimiter, the number of levels that users will be able to identify reduces if given the same maximum deformation.

However, even with the help of the tactile delimiter to indicate maximum distance, participants overestimated the distance that they needed to travel for every task. Our experiments do not offer any evidence on why such systematic overestimation is occurring. We speculate that this could be an indication that the users are simply poor at distance estimation given these target distances, or that there was not enough compliant force feedback for participants to estimate the required distance. Nevertheless, more research on this aspect of deformable surfaces is necessary in order to determine the explanation of these phenomena.

Another interesting finding is that, even for flat surfaces, requiring users to push into the surface to deform it causes them to change the position of their finger. While the offset error is not large (within 2mm), it may be enough to cause a selection error if the target requires too much deformation. Additionally, the shape of a device not only affects the participant's ability to point precisely, but also to precisely deform the surface. Greater inclines for travel resulted in less accuracy for positions, but increased accuracy for deformation distance. This indicates that compensation or even some sort of visual feedback is necessary to achieve higher levels of accuracy overall. To avoid that, it is possible to use the method in [16] to calculate a minimum button size for a user by taking into account the surface deformation.

An alternative solution for the position problem is to move the projection surface. For example, the projection surface might not have to be on the deformable surface (latex), but instead on the hard surface underneath it. With head-tracking and a translucent surface on top, it could even be possible to use motion parallax to create the illusion that the target is in between both surfaces. We speculate that such approach could increase the final touch position accuracy, but reduce the overall path accuracy. However, further investigation and comparison with the approach used in this paper is necessary.

In addition, as mentioned earlier, our system was designed for experimenting and investigating how touch is affected by surface deformation. The surface material (latex) is not ideal for many types of interactions (e.g., sliding your finger when the surface is deformed). The form of the flat surface results in non-uniform distribution of tension. In this case, it means that the center produces less compliant force feedback than any other point of the surface, and the closer the user is to the edges, the more tension will be generated in the direction of that edge. The use of LEDs and illumination for determining deformation distance requires very precise and careful calibration, and the use of a wide-angle lens for the flat surface is less than ideal since resolution towards the edges is reduced. Different solutions for these problems should be found before moving efforts on to making new interactions.

Finally, we believe that this paper provides initial evidence on the feasibility of using deformable flexible surfaces for touch interaction. While previous work focuses on possible applications and basic interactions, we show what problems arise when deformation is used as an additional dimension, and discuss how to avoid or minimize them. Our approach was to investigate some of the core issues of performing touch interactions on a deformable surface, particularly when trying to account for a specific deformation. Because devices like these do not exist beyond research labs and there are only a few applications for them, we believe it is premature to discuss the canonical tasks for deformable surfaces.

In the future, we plan to evaluate other features of deformable surfaces, such as compliant force feedback, different distances for the tactile delimiter, and also design and evaluate new interactions with deformable surfaces.

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