Exploring Multi-touch Contact Size for Z-Axis Movement in 3D Environments

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ABSTRACT

In this paper we examine two methods for using relative contact size as an interaction technique for 3D environments on multi-touch capacitive touch screens. We refer to interpreting relative contact size changes as "pressure" simulation. We conducted a 2 x 2 within-subjects experimental design using two methods for pressure estimation (calibrated and comparative) and two different 3D tasks (bidirectional and unidirectional). Calibrated pressure estimation was based upon a calibration session, whereas comparative pressure estimation was based upon the contact size of each initial touch. The bidirectional task was guiding a ball through a hoop, while the unidirectional task involved using pressure to rotate a stove knob. Results indicate that the preferred and best performing pressure estimation technique was dependent on the 3D task. For the bidirectional task, calibrated pressure performed significantly better, while the comparative method performed better for the unidirectional task. We discuss the implications and future research directions based on our findings.

Index Terms: H.5.2 [Information Interfaces and Presentation]: User Interfaces—Input devices and strategies; I.3.6 [Computing Methodologies]: Methodology and Techniques—Interaction techniques

1 INTRODUCTION

Multi-touch interfaces, especially those using capacitive input, which relies on the electrical properties of the human body to detect touch, are now prolific in the use of monitors, laptops, tablets, and phones. Further, many of these displays offer 3D capabilities, as evidenced by more releases of 3D apps, games, and maps. With these new trends in user adoption of multi-touch interfaces for 3D interaction, the need for intuitive and accurate multi-touch gestures for 3D environments becomes increasingly necessary. However, designing multi-touch gestures for 3D environments presents an interesting set of challenges since input surfaces are inherently 2D. We propose using pressure simulation techniques as a way to convey depth and/or force within 3D gesture interactions. Specifically, we use variations in finger contact size (i.e., the surface area of the finger which comes into contact with the input surface) as a way to simulate "pressure" and translate it into meaningful 3D interactions. Since varying contact size is very similar to varying pressure and acts as a suitable metaphor, we use the term "pressure simulation". Since there are no pressure sensors on capacitive touch screens, we are instead interpreting changes in contact size by varying finger tilt angles, where larger contact size corresponds to heavier "pressure".

While large bodies of work exist respectively in the areas of gesture recognition [24, 28], multi-touch capacitive interfaces [1, 3, 12, 25], pressure simulation [2, 4], and 3D virtual environments [10, 19], very little, if any, existing work focuses on the

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Figure 1: Our experiment apparatus included a 55-inch Perceptive Pixel display raised to standing height and tilted upwards by 30 degrees.

intersection of these research areas. Thus, we conducted a 2 x 2 within-subjects experiment of 20 participants examining two different pressure simulation techniques (calibrated and comparative) with two different 3D tasks (bidirectional and unidirectional). Our goal was to determine users perceptions (i.e., ease-of-use, gesture fit, and perceived efficiency) and actual performance (i.e., total completion time). To the best of our knowledge, no previous studies have examined using pressure or contact size for multi-touch object manipulation. In addition, no previous studies have compared calibrated or comparative pressure estimation techniques.

In this paper, we first explain how our work builds upon the existing literature. Then, we provide a detailed description of how we calculated pressure estimation from contact size. We then describe our research design. Finally, we present our results, rationalize why this unanticipated result occurred, discuss the implications, and offer suggestions for future work in multi-touch pressure simulation techniques for 3D object manipulation.

2 RELATED WORK

2.1 Non-Capacitive Sensing Pressure Estimation

Since any use of touch inherently uses pressure, there have been many investigations into incorporating pressure information into surfaces by using malleable materials, such as with liquid displacement sensing [14]. Early work investigating pressure as computer input began with Herot and Weinz in 1978 [13], followed by Buxton concluding in 1985 that pressure control without feedback (i.e a button click) can be difficult but it is a promising research area [6]. Since then there have been several investigations into using pressure sensors as input [26], what pressure force levels are comfortable for users [21], and how many levels are distinguishable [23]. There have also been investigations into augmenting mobile devices with pressure sensors [5, 7, 20, 23]. PointPose doesn't simulate pressure as we do with touch contact size but does detect the pose, rotation and tilt of a finger on a surface using a depth camera [18].

Since most of today's widely used multi-touch devices, whether mobile or desktop, use a capacitive sensor matrix that does not allow

(a) The bidirectional task required guiding a ball through 3 hoops by translating while applying pressure for depth control.

(b) The unidirectional task required rotating a stove top knob with the index finger and thumb to a certain position while applying pressure past a threshold.
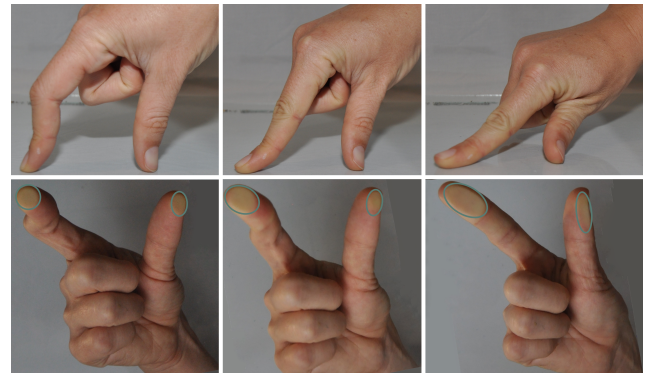
Figure 2: The bidirectional and unidirectional tasks.

(a) Light "pressure"   (b) Medium "pressure"   (c) Heavy "pressure"

Figure 3: Different pressure levels shown from the side and the bottom. The two finger position could be used in the stove top task.

for actual pressure input, we chose to focus on the feedback available from capacitive devices. The drawback of capacitive devices is that they only report the contact size based upon pixel coverage and are not capable of sensing pressure forces. Liquid displacement sensing would allow for more exact pressure sensing, and even vision-based systems can do better than capacitive by using the contact point's brightness [4]. Recently, Apple began incorporating their force sensor and Force Touch gestures into mobile phones and track-pads, but the gestures are used mainly for simple desktop selection operations, not for applying force during movement [16]. However, even if high accuracy pressure sensing components were made widely available, it would make some actions very difficult as pressure increases the touch's friction on the surface.

2.2 Capacitive Sensing Pressure Simulation

We use the term pressure "simulation", since there are no pressure sensors on capacitive touch screens. There have been some pressure estimation techniques targeted at capacitive mobile devices that try to capture actual pressure by proxy techniques. For example, Pseudo-pressure is a pressure estimation method which assumes increases in pressure create both jitter in contact locations as well as increased touch duration [1]. This technique was used as a way to reject text entry suggestions on mobile phones. However, Pseudo-pressure's jitter would not be reliable on a large screen, especially when applying pressure during another translation or rotation gesture. The time duration would also not be applicable for the 3D tasks we are evaluating. Vibpress utilized a mobile device's built-in microphone to detect five different pressure levels by using different sound amplitudes [15]. Forcetap analyzed acceleration data along the z-axis to differentiate between a strong tap and a gentle tap on touch screens [11]. All of these methods are limited because they focus on mobile applications and aren't applicable for applying pressure during translation or rotation.

As a way of simulating pressure on capacitive devices, there have been several developments that take advantage of changes in contact size, as we do in our work. As explained in [4], contact size can be altered by either pressure or finger-tip angle. However, applying more or less pressure on a rigid surface will only slightly change the contact size. Thus, finger-tip angle is what we focus on in our work. An example of a multi-touch technique that takes advantage of contact size is Sim-Press which simulates clicking by mapping the changes in the finger's contact area to changes in pressure [2]. Similarly, Fat Thumb is a mobile technique for one handed zooming that uses increases in the thumb's contact size to trigger different zoom levels [4]. Another technique that uses the finger-tip angle in multi-touch interaction is Microrolls. Microrolls doesn't imitate pressure as Fat Thumb and SimPress

do, but instead interprets small rocking movements of the thumb to trigger gestures without requiring any tangential movement [25]. Similar to Microrolls, Thumbrock [3] and Shear Force [12] interpret different actions or forces based upon the change in orientation of the finger.

We build upon this existing work in the following ways: First, similar to FatThumb and SimPress, in both of our estimation techniques we interpret relative changes in contact size as a way to estimate pressure. However, both of their approaches require calibration to determine passing a threshold point. We also examine an alternative technique: comparative pressure estimation, which knows nothing of the user's calibration contact size only their initial touch's contact size. Second, FatThumb and SimPress look at contact size as a threshold to activate either clicking or zooming modes, whereas we map pressure continuously to depth position. Third, these studies focus on mobile and/or GUI settings in 2D tasks; we focus on contact size changes during multi-touch interaction within 3D virtual environments. Finally, we also apply the two pressure estimation techniques to different 3D tasks that vary in the dexterity required by the users (unidirectional versus bidirectional).

2.3 Multi-touch Interaction for 3D Environments

There is some existing work in 3D multi-touch interaction, most of which require multiple fingers or hands. Martinet designed zTechnique for 3D positioning using a single view of the scene [19]. Using the zTechnique, an object is selected using the first finger (direct), depth positioning is then controlled by a second finger on the other hand (indirect). Reisman created a technique which mimics the 2D RST paradigm in 3D by using a constraint solver to maintain connection between the touch points and the corresponding points on the object during 3D rotations and translations [24]. Hancock's Sticky Fingers separates translation and rotation tasks by allowing 1, 2 and 3 finger direct manipulation techniques [10]. Wilson took a different approach with a physics based solution that used particle proxies in the scene to simulate grasping behavior [28].

To our knowledge, there has not been any work on pressure simulation and its applications to 3D environments. All of the previous work cited on simulated pressure focuses on mobile applications with mainly text entry or 2D applications. In this paper, we focus on using pressure as an interaction technique for 3D environments in order to create realistic gestures and to easily allow a third dimension for object translational or rotational manipulation. By adding simulated pressure to touch input, we expand upon these existing 3D multi-touch manipulation techniques.

3 PRESSURE ESTIMATION TECHNIQUES

Before we discuss how we calculated simulated pressure, we must explain what we mean by "pressure". If the user applies more actual pressure force down onto the screen in the position shown in Figure 3a, and then applies light force, the difference between capacitive readings will be negligible. Capacitive sensor reading only reflect the amount of skin in contact with the screen, not the downward force. Any increased displacement of finger skin by increasing force would be negligible (as also discussed in [4]). Thus, our interpretation of "pressure" is really controlled by increasing and decreasing contact area with the screen by changing the pitch, or tilt, of the fingers as shown in Figure 3. Since most fingers can't bend far backwards on the interphalangeal joints, they are limited by flexion alone and must change the pitch of their whole finger (shown in Figure 3).

Our experimental application uses Windows Touch Input Messages, which report the x, y position, time, xContact (width of the touch contact area), and yContact (height of the touch contact area) reported in hundredths of a pixel in physical screen coordinates. The Windows Touch events do not report the major or minor axis of the touch area, or the rotation of a touch. Thus, the interpreted bounding box using xContact and yContact could be calculated as slightly smaller than actual size for rotated hand positions. We do not have a current solution for this, but this could be improved upon by using slight positional changes to estimate the touch's rotation. For all of the contact size readings below, we calculate $currentsize$ as $\sqrt{xContact * yContact}$.

We explored two different pressure estimation techniques, calibrated pressure and comparative pressure, which both use the contact size of a touch point on a screen. The difference between methods is how they determine the neutral pressure value from which to compare corresponding increases and decreases in pressure. For both methods increases in contact size are interpreted as more simulated pressure within our defined metaphor. More pressure then corresponds to more depth movement into the environment since more force usually moves something away.

Calibrated pressure requires the user to calibrate their light, medium and heavy pressure contact sizes and then calculates an average neutral contact size. Our calibration exercise presented the user with a cube and asked them to press on it 5 times using their index finger (on the center and 4 corners) for light pressure, medium pressure, and then high pressure. Each participant was told that pressure was interpreted as contact size. It was then demonstrated that light pressure meant the tip of the finger, hard pressure meant the full pad of the finger, and medium pressure meant about halfway between the two. The neutral pressure was then calculated as the mean contact size of all of the collected contact sizes. Since capacitive screens start registering touches as they come into contact with the screen, the screen will register a few very light touches before the intended interaction begins. During our pilot study we determined that ignoring the first five events was appropriate to only record the intended interaction contact size.

For the calibrated method, the current pressure was calculated as the relative difference in area of the current touch's contact area from the saved neutral contact area:

$$((currentsize - neutralsize) - minimumsize)/neutralsize$$

For example, for a user that has minimum, neutral, and maximum values of 500, 1800, and 4100 their pressure range would be ((500-1800)-500)/1800, ((4100-1800)-500)/1800 = (-1, 1). Since we take the average of all of their calibrated values the range is approximately (-1, 1). Thus, for increases in contact size, the pressure is positive, and for decreases in contact size the pressure is negative. The positive and negative pressure is useful for controlling bi-directional depth position, or z axis translation, where heavier than neutral pushes the object into the screen (away from the camera) and lighter than neutral pulls the object towards the user (towards the camera).

Comparative pressure was also calculated as the difference from neutral pressure, where the initial touch is assumed to be neutral and the minimum size is unknown:

$$((currentcontactsize - neutralsize))/neutralsize$$

For the same user, assume their initial touch is 500 (which also happens to be their minimum) then their range is (500-500)/500, (4100-500)/500 = (0, 7.2). This range not only eliminates negative pressure, but it skews positive pressure. In our application, this would allow the user to increase pressure at a faster rate and pass the pressure limit they would have had with the calibrated method. Then assume the same user has an initial touch of 4100 (which is their maximum) then their range is (-7.2, 0). Thus, if the user would like to move in a certain direction faster, skewing their neutral value in the opposite direction would be advantageous. However, if the user wants reliable bi-directional movement they would need to start with medium pressure.

4 STUDY DESIGN

4.1 Independent and Dependent Variables

We implemented a 2 x 2 (estimation method x task type) repeated measures, within-subjects experimental design. The independent variables were the estimation methods - calibrated and comparative - and the task types - bidirectional and unidirectional. The bidirectional task required translation while varying pressure in order to guide a ball through hoops (shown in Figure 2a). The unidirectional task required rotation while maintaining pressure to push in and turn a knob (shown in Figure 2b). The dependent variables for all conditions within our experimental design included: 1) three perceived measures based on user ratings of ease-of-use, goodness of gesture fit, and perceived efficiency to complete the task, and 2) an objective measure of Task Completion Time (TCT). For the perceived measures, after each task participants were asked to answer the following questions using a 7-point Likert scale, based on previous work [29]:

- How easy was it to perform the gesture?

- The gesture I used was a good match for the task.

- I quickly completed the task.

TCT was measured as seconds to complete the task trial. The trial started when the user pressed a "Begin" button and automatically ended when the system detected the user had completed the task.

4.2 Participants and Apparatus

We recruited 20 participants (7 female, 13 male) ranging in age from 18 to 29 years (average: 20.9 years). Of the 20 participants, 13 owned a touch screen phone while the other 7 owned both a touch screen phone and tablet. All participants received $10 as compensation for their time. We conducted the experiment on a 55-inch Microsoft Perceptive Pixel display. The display was mounted on a stand so the bottom edge of the display was raised to 3.5 feet, approximately standing height, as shown in Figure 1. The display was tilted upwards by 30 degrees since tilted displays have shown to be for comfortable for users [22]. The apparatus also included a camcorder capturing the screen and the participant's arm and hand, and a table for the investigator to observe and take notes. Our application used Windows Touchinput events which return xContact and yContact properties in hundredths of a pixel in physical screen coordinates for both pressure estimation techniques [8]. We developed the 3D environment and user study application in the Unity3D game engine.
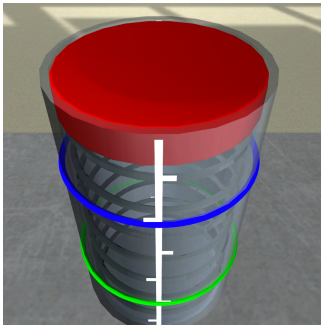
Figure 4: User had a practice session where they applied increasing and decreasing pressure levels on a 3D spring-loaded button.
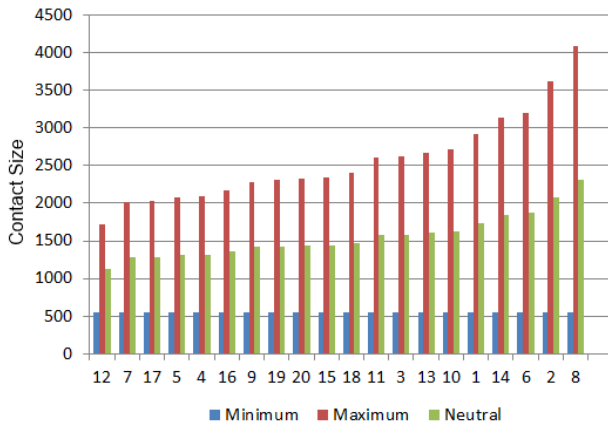

Figure 5: Results of each user's calibration session: the minimum and maximum contact sizes and the calculated calibrated neutral pressure values for all users, ranked from low to high in hundredths of a pixel.

4.3 Tasks

We wanted to ensure that our results for the different pressure estimation techniques could readily be generalized to 3D tasks that utilized both unidirectional and bidirectional movement. As such, we applied our pressure simulation techniques to two different tasks: (1) a bidirectional task where users guided a ball through hoops arranged at different depths and (2) a unidirectional task where users applied pressure while rotating a stove knob (shown in Figure 2a and Figure 2b).

In both 3D tasks, pressure was being varied with the tilt of the fingertip to estimate pressure. The bidirectional task controls x and y translational position with the position of the touch point, and at the same time, the finger tilt variations controlled depth (z) position. Harder than neutral pressure increased the depth position away from the camera, lighter than neutral pressure decreased depth position towards the camera, and neutral pressure maintained depth position. The greater the pressure above the neutral value, the faster the ball moved away, and vice versa for pressure below the neutral value. In the ball and hoops task, pressure acts as an alternative to the pinch to zoom method used in Sticky Fingers for depth translation [10].

The unidirectional task requires pushing in a stove top burner knob by surpassing a pressure threshold and maintaining that pressure while rotating the knob. This task also requires using the thumb and index finger to rotate. We examine pressure to control depth while rotating in the stove top burner task, where a pressure threshold has to be met in order to push the stove top knob prior to rotation.

4.4 Procedure

Before participants began the experiment, the proctor explained to them what they were going to explore during the experiment. The proctor explained that they would be translating and rotating different objects on the screen, but to control depth position contact size would be used. Contact size was explained as being similar to increasing and decreasing pressure, but is actually controlled by the tilt of the finger. The proctor demonstrated varying pressure levels while they were explained. Then, after each participant understood what we were measuring they began the study with the calibration session.

Next, users had a practice session where they applied increasing and decreasing pressure levels on a 3D spring-loaded button, shown in Figure 4. This allowed users to experience how finger tilt was interpreted as pressure. Following the calibration and practice sessions, participants were presented with the experimental tasks. The bidirectional and unidirectional tasks were each completed with both calibrated and comparative pressure estimation techniques, totaling four trials overall. To prevent ordering effects, half of the participants completed the bidirectional task first and half completed the unidirectional task first. The order of the estimation methods was also balanced within each task.

Before each trial, participants had a practice session to get comfortable with each combined task and estimation method. They were asked to practice the entire task at least twice or until they were comfortable performing the task. Since participants practiced the task multiple times, there were no repeated trials. Once the trial began, participants were instructed to complete the task as quickly as they could since each trial was timed. Following each trial, they were asked the three survey questions on ease-of-use, goodness of gesture fit, and speed. To test our hypotheses, we first used a Friedman test followed by a Wilcoxon signed rank test for the perceived dependent measures: Easiness, Goodness and Perceived Speed ratings. Then, a two way repeated measures ANOVA was used, followed by a paired-samples t-test, to assess the differences in the actual task completion times (TCTs).

4.5 Hypotheses

Since the calibrated pressure can immediately classify a user's pressure level in the range from low to high instead of only being able to interpret relative increases and decreases as the comparative method does, the following hypotheses reflect our expectation that the calibrated method will be perceived as better by users and outperform the comparative method for both tasks:

H1 The calibrated pressure estimation method will be perceived as significantly (a) easier to use, (b) better fit to the gesture, and (c) faster than comparative estimation technique.

H2 The Time to Complete (TCT) the tasks for the calibrated pressure estimation technique will be significantly faster than the comparative pressure estimation technique.

5 RESULTS

5.1 Calibrated Neutral Pressure

We found a wide spread of calibration values from our participants, demonstrating the utility in calibration. The minimum pressure values, maximum pressure values and the calibrated neutral pressure values for all users is shown in Figure 5, ranked from low to high. Interestingly, each user had the same minimum pressure value indicating a limitation in the sensor for exact sensing. The overall average neutral pressure is 1555.94 (stdev = 293.00). We can see from these values that there is a large difference in pressure sizes from the minimum calculated neutral value (1130.45) and the maximum calculated neutral value (2316.269), the maximum value is almost 2 times as large. In addition, the maximum contact size for

	Easiness	Goodness	Perceived Speed	TCT
Bidirectional Calibrated	**6.30 (0.86)**	**6.45 (1.09)**	**6.30 (0.80)**	**34.27 (23.00)**
Bidirectional Comparative	5.30 (1.17)	5.95 (1.36)	5.15 (1.31)	50.61 (35.39)
Unidirectional Calibrated	4.20 (1.85)	5.30 (1.78)	5.15 (1.31)	29.35 (27.53)
Unidirectional Comparative	**5.55 (1.39)**	**6.00 (1.08)**	**5.85 (0.99)**	**16.09 (13.80)**

Table 1: The averages and (standard deviations) of our dependent measures: ease-of-use, gesture fit, perceived efficiency, and task completion time (TCT). The bold highlights how the Calibrated method's ratings were higher and TCT were faster than the non-bold Comparative ratings for the bidirectional tasks. The bold also highlights how the Comparative method's ratings were higher and TCT were faster than the non-bold Calibrated ratings for the unidirectional tasks.

	Wilcoxon Signed Rank Test			Paired Samples t-test
	Easiness	Goodness	Perceived Speed	Task Completion Time
Bidirectional (Calibrated vs Comparative)	**z = 3.27, p<.001**	**z = 2.23, p<.026**	**z = 3.22, p<.001**	**t_{19} = 3.03, p<.007**
Unidirectional (Calibrated vs Comparative)	**z = 2.35, p<.019**	z=1.67, p = .094	**z = 2.23, p<.026**	**t_{19} = 2.28, p<.034**

Table 2: For the perceived measures (easiness, goodness, perceived speed), we used a Wilcoxon signed rank test to compare the Calibrated ratings to the Comparative ratings within the bidirectional and unidirectional tasks separately. We also used a Paired samples t-test to compare the Task Completion Times for the Calibrated and Comparative methods within the bidirectional and unidirectional tasks separately. The bold highlights the significant results.

the user with the smallest overall contact sizes (1716.39) is less than the calculated neutral value for the user with the largest overall contact sizes (2316.27). The user with smallest overall values would have a hard time using the system calibrated for the user with the largest values or even the median values.

5.2 Hypotheses Testing Results

Our hypotheses for the perceived measures were, H1 (a,b,c), that users would prefer the calibrated method over the comparative method for both tasks as demonstrated by Easiness, Goodness and Perceived Speed ratings. In order to evaluate our results, we performed a Friedman test which showed significance for Easiness $\chi^2(3) = 19.66, p < .0005$, Goodness $\chi^2(3) = 7.62, p < .05$, and Perceived Speed $\chi^2(3) = 22.84, p < .0005$.

We then tested the results for the bidirectional and unidirectional tasks separately using a Wilcoxon signed rank test, the results of which are shown in Table 2. As shown in Table 1, all of the perceived measures are higher for the Calibrated method than the Comparative method, for the bidirectional task only. For the bidirectional task, the results of the Wilcoxon signed rank tests demonstrated that the Calibrated method was perceived as significantly better overall for easiness (z = 3.27, p<.001), goodness (z = 2.23, p<.026), and perceived speed (z = 3.22, p<.001) than the Comparative method. Thus, the Wilcoxon signed rank test confirmed H1 (a,b,c) for the bidirectional task only.

For the unidirectional task, all of the perceived measures were higher for the Comparative method than the Calibrated method (as shown in Table 1), which is the reverse of H1 for the unidirectional task. The results of the Wilcoxon signed rank tests for the unidirectional task were significant for the Easiness (z = 2.35, p<.019) and Perceived Speed ratings (z = 2.23, p<.026), but not for the Goodness ratings (z=1.67, p = .094). Thus, we found that the H1(a,b,c) hypotheses were only true for the bidirectional task (shown in Table 3) and, interestingly, the reverse was true for the unidirectional task.

For hypotheses H2 we believed users would also have faster task completion times (TCT) using the calibrated versus comparative method for both tasks. We tested Hypothesis H2 using a two-way repeated measures ANOVA and found there were main effects for Task type $F_{1,19} = 24.54, p < .0001$ but not for Pressure estimation method $F_{1,19} = .25, p < .62$, and there were interaction effects for
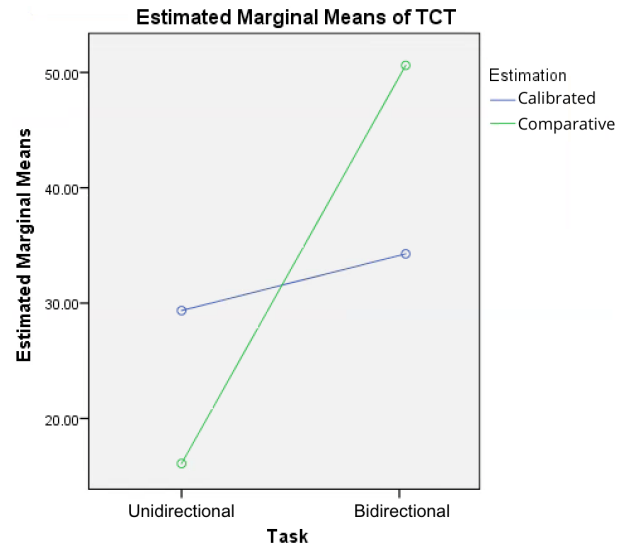

Figure 6: The Two-way repeated measures ANOVA interaction graph for Task Completion Times (TCT) for Task*Estimation Method.

Task*Estimation $F_{1,19} = 9.97, p < .005$ as shown in Figure 6. As shown in Table 1, the calibration method had faster times than the comparative method, for the bidirectional task only. We then used a Paired-samples t-test separately for the bidirectional and unidirectional tasks to examine these interaction effects (shown in Table 2). We were able to confirm H2, that the calibration method performed significantly faster (t_{19} = 3.03, p<.007), but for the bidirectional task only. However, we again proved the reverse of H2, the comparative method performed significantly faster (t_{19} = 2.28, p<.034), for the unidirectional Task.

Tasks	Hypotheses	Results
Bidirectional	**H1a:** Ease-of-use, Calibrated >Comparative	ACCEPT
	H1b: Goodness-of-fit, Calibrated >Comparative	ACCEPT
	H1c: Perceived Speed, Calibrated >Comparative	ACCEPT
	H3: TCT Calibrated <Comparative	ACCEPT
Unidirectional	**H1a:** Ease-of-use, Calibrated >Comparative	REJECT
	H1b: Goodness-of-fit, Calibrated >Comparative	REJECT
	H1c: Perceived Speed, Calibrated >Comparative	REJECT
	H3: TCT Calibrated <Comparative	REJECT

Table 3: A summary of results based upon our initial hypotheses.

6 DISCUSSION

6.1 Interpreting Our Results

While we found mixed support for our initial hypotheses, the results from our study were even more insightful than if we had achieved the outcomes we had originally set forth in our hypotheses. Indeed, we found that *different* pressure estimation techniques perform *significantly* better for different 3D tasks based on the type of task users have to perform. Because of the unanticipated results, we were challenged to reflect on our user study and the lessons we learned from our users. Here, we present some of those insights to help explain our results.

As anticipated, the bidirectional task benefited from the calibrated pressure estimation technique for a number of reasons. First, bidirectional control required a predictable neutral position, which users were able to achieve through calibration. Second, the finger's orientation was roughly the same during both the calibration session and the bidirectional task. Thus, users were able to leverage a wider range in contact size. In contrast, the comparative pressure took the first touch as the neutral position. If the user started with either a light or hard touch, this set their neutral point as either light or hard, which limited them to not being able to go any lighter or harder during the ball and hoops task. This was a limitation of the comparative pressure in the bidirectional task, since it would make it impossible to move the ball towards the camera in the bidirectional task. Thus, if the user wanted to bring the ball towards the camera, they would have to let go of the screen and initiate their interaction again with a harder touch and then transition to light pressure. However, in the unidirectional task where a pressure threshold needs to be met, as in the unidirectional task, it would make it easier to apply positive pressure past this threshold if the initial touch was very light.

Yet, we discovered the unexpected result that comparative pressure estimation was significantly better than calibrated pressure estimation for the unidirectional task. We believe that the unidirectional task benefited from comparative pressure for a number of reasons. From previous pilot testing, we determined the pressure threshold before the knob would depress to be positive 0.5 pressure units. Some users' fingers did not flex in a way for them to be able to surpass their calibrated threshold without putting their fingers into an unnatural or uncomfortable position. Also the orientation of the user's fingers changed as they were rotating which made it difficult to maintain pressure past the threshold value during rotation. Whereas with the comparative pressure (as discussed in Section Pressure Estimation Techniques) the user can reach a higher pressure value simply by starting with a very light pressure. Users learned that starting with light pressure for the comparative method was effective during the practice session. Users were then able to understand how to make the comparative method work for them during the actual task trial. If the users were unable to get the neutral position right for the rotation task on their first try, the comparative estimation technique allowed them to readjust each time they touched the screen. We believe that because the unidirectional task finger posture was more difficult for some users, the ability to readjust with trial and error was an invaluable benefit to users.

6.2 Implications for Design

There are five important design implications that come out of this work. First, different estimation techniques are more optimal for different types tasks. Therefore, intelligent interaction designs could be used to customize the pressure estimation technique based on the different motions being performed by the users in order to optimize the user experience. Second, more specific calibration may be necessary for unidirectional tasks. The same large pressure variation range available to a user when calibrating with their finger straight up and down, is not available in tasks that (1) use the thumb, (2) have a small area, and (3) require rotation. The third implication is that bi-directional movement has more constraints than uni-directional movement. It is more important to bi-directional movement to determine where the neutral, low and high pressure values are, making calibration more necessary. The fourth implication is that the user needs to know more about the implementation of the pressure estimation when calibration is not used. Unidirectional movement can get by better without calibration, but only if the user understands that applied pressure is interpreted as increases in contact size and that applying steady pressure outright will not work. Finally, if calibration or pressure estimation customization is not possible in a complex task that requires both bidirectional and unidirectional movement, then it would be best to use the comparative estimation technique. The comparative pressure estimation technique performed more consistently across both tasks, though sub-optimally for the bidirectional task. In addition, we also believe that it may not be necessary for every user to go through the calibration process and that an average calibration range would work well for most users.

6.3 Limitations and Future Work

There were a few limitations with our study design that we would like to address in future work. First, we chose two different tasks, but we also have two types of input methods; one uses a single finger and the other uses a finger and thumb, which presents a confound. In addition, the second technique requires a twisting motion, whereas the first does not. In future work, we would like to compare two similar tasks with a single variable to verify our findings.

Secondly, the fact that each user was shown how light pressure meant the tip of the finger, hard pressure meant the full pad of the finger, and medium pressure meant about halfway between the two, meant that an understanding of the underlying simulation mechanism was necessary. This enabled interaction with the system by changing the finger postures without really changing the pressure levels. We would like to investigate further into whether participants really changed the pressure levels, the finger postures, or a combination of the two. In addition, we would like to examine how users' touch properties change with varying pressure levels to see if the pressure simulator does not have to rely on a user being aware of changing

their finger posture.

Finally, our user study was comprised of a relatively small and homogeneous sample of participants. Therefore, further studies need to be done with larger populations, especially those who have sensorimotor skill limitations, so that these findings can be generalized to all users and/or those with special needs.

In future work we would like to identify the best calibration approach for pressure simulation to be used for a wide variety of tasks. One approach could be defining a finger pad descriptor, where the contact size range of each finger is measured under different circumstances such as one finger alone, adding the thumb, grasping a small area, or rotating. An alternative approach would be performing calibration specific to each bidirectional or unidirectional task. We would also like to evaluate how well an uncalibrated user can use the calibration technique with an averaged calibration range from different users. In addition, we would like to examine how pressure could be used in simulating grasping behavior as Wilson et al. had done with proxy particles in the scene [28]. Finally, we plan to determine whether pressure simulation can benefit multi-touch training or rehabilitation applications as compared to traditional methods.

7 CONCLUSION

We evaluated the two pressure estimation techniques, calibrated and comparative, and their applications to different tasks in a 2x2 within-subjects experiment. Although we expected the calibrated pressure estimation technique to outperform the comparative technique, we found that our initial hypotheses were only partially supported. Instead, we uncovered an insightful and unanticipated finding: different pressure estimation techniques are significantly better for different tasks based on the type of depth control being performed. This motivates future research in intelligent designs for dynamically choosing pressure simulation techniques for multi-touch 3D user interactions that optimize the user's experience.

8 ACKNOWLEDGMENTS

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