Understanding the Ergonomic Constraints in Designing for Touch Surfaces

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ABSTRACT

While most current interactive surfaces use only the position of the finger on the surface as the input source, previous work suggests using the finger orientation for enriching the input space. Thus, an understanding of the physiological restrictions of the hand is required to build effective interactive techniques that use finger orientation. We conducted a study to derive the ergonomic constraints for using finger orientation as an effective input source. In a controlled experiment, we systematically manipulated finger pitch and yaw while performing a touch action. Participants were asked to rate the feasibility of the touch action. We found that finger pitch and yaw do significantly affect perceived feasibility and 21.1% of the touch actions were perceived as impossible to perform. Our results show that the finger yaw input space can be divided into the *comfort* and *non-comfort* zones. We further present design considerations for future interfaces using finger orientation.

Author Keywords

Finger orientation; touch; surface; mobile; ergonomics; pitch; yaw; ergonomic zone; non-comfort zone.

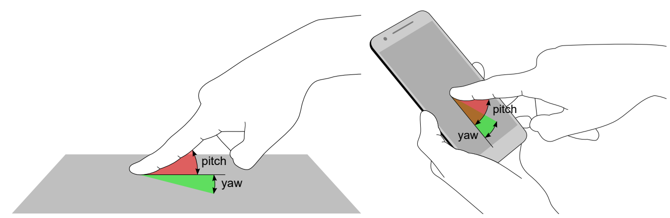
ACM Classification Keywords

H.5.2 User Interfaces: Ergonomics

INTRODUCTION

The age of ubiquitous computing has brought a large number of interactive surfaces into our lives. Interactive surfaces are present in various forms, and various contexts from tabletops to mobile devices, and touchscreens continue to remain the main input technique. In current systems, a finger touching a screen or surface is typically reduced to simple two-dimensional coordinates. A large body of research proposes to enrich such a touch interaction. In particular, previous work suggests using the orientation of a finger touching a surface as a means of input. For example, Wang et al. [23] adapted menus to finger orientation, Takeoaka et al. [21] used the angle of finger pitch as an input parameter, and Kratz et al. [14] enabled 3D touch gestures. A number of commercial systems, including devices by Multitaction[1] and the Microsoft Surface Hub[2] are now able toangle of finger pitch as input parameter sense the finger orientation and the angle of approach on an interactive surface.

While previous work has suggested compelling ways to use the finger orientation as input and technology that cangle of finger pitch as input parameteran sense the orientation is now available, common commercial systems do not yet use finger orientation as part of the interaction. One reason is that the orientation of the finger is restricted by the physiological constraints of the user's hand. Considering a flat surface in



(a) Tabletop (b) Mobile devices

Figure 1. Examples of finger orientations on an interactive tabletop (a) and in a mobile setup (b). Finger orientation input with pitch and yaw input can enlarge the input space for tabletops as well as for mobile devices.

[1] `multitaction.com` last accessed: 05-17-2017
[2] `microsoft.com/microsoft-surface-hub/` last accessed: 05-17-2017

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front of a user, there are finger orientations in which touch is uncomfortable or even impossible to perform. As not all finger orientations can be used for the input, it is important to learn about users' restrictions when designing orientation-aware input techniques.

We propose readdressing the ergonomics of single-finger touch on interactive surfaces by investigating how systems can effectively use different finger orientations. In this paper, we look closely at different finger orientations to understand the limitations they impose on the touch action. We systematically vary pitch and yaw configurations (see Figure 1) to determine which finger orientations are optimal for touch interactions and when users find it feasible to perform the touch action. To that end, we conducted a study where participants rated the perceived feasibility of the touch action when the finger pitch and yaw were varied independently. In a controlled experiment, we used pitch stabilizers to test 4 pitch values and 16 equally spaced yaw angles. Our findings indicate that pitch and yaw do significantly affect perceived feasibility to perform a touch action. Further, we found that there is a subset of yaw angles at which users are comfortable performing touch actions, the *comfort* zone. Outside of this zone is the *non-comfort* zone, where the touch action is perceived to require significantly more effort, and some touch actions were found to be impossible to perform. Based on these results, we discuss design considerations for using finger orientation input in future applications.

To summarize, this paper contributes the following:

1. A systematic study of the perceived feasibility of a touch action with respect to finger pitch and yaw;

2. A characterization of the *comfort* and *non-comfort* zones for finger yaw input;

3. Design considerations for using finger orientation as an input modality.

In the following sections, we review previous work that addresses the nature of touch on interactive surfaces. We then present the details of our study design and the results of the experiment. Next, we interpret and discuss the implications of the data obtained. Finally, we present how our findings help to design future applications.

RELATED WORK

Enlarging the input space on touch devices has been the subject of a body of research. In this section, we provide an overview of research on touch input techniques as well as research addressing the ergonomics of touch.

With the the success of mobile devices, touch-based interaction has become the dominant way of interacting with technology. However, compared to the use of indirect interaction techniques such as mouse, direct touch poses certain challenges. One such problem found by Siek et al. [20] is the *fat finger problem*. Holz and Baudisch further found that there is an offset between the point where the user assumes to have touched the surface and their actual finger position [12, 13]. They found that the touch offset is influenced by the angle of finger approach, and concluded that touch is not a 2-dimensional interaction technique, but is a 3-dimensional one. They showed that direct touch needs to be described by the 3D finger orientation with respect to the touch surface for pitch and roll gestures.

Common touchscreens only provide the 2D position of the fingers on the screen. To enrich the information gained from touch, a number of approaches have been proposed. Android, for example, enables access to the context menus with a *long press* and thereby uses dwell time as an additional input parameter. With a similar motivation, Boring et al. [2] presented the *fat thumb* interaction technique, where the size of the touch can be used as an input parameter. Heo and Lee [10] proposed using force to augment touch and considered both normal and tangential forces. Recently Apple introduced *3D touch* to extend the interaction space of touch input. However, in 2008 Cao et al. [3] had already proposed ShapeTouch; a system where the shape of the hand modifies the action triggered when a touch occurs. Further, Goyal [5] builds upon that work to propose that shape-bending can also offer a novel vocabulary to a wide variety of 3D gestures that simulate touch, as an alternative to yaw and pitch. As is evident, significant avenues are being constantly pursued to identify possibilities beyond the action of touch itself.

Focusing specifically on fixed horizontal surfaces like tabletops, Wang et al. [23] have proposed to adapt menus to finger orientation, e.g. for pie and torus menus. Finger orientation was also considered for creating novel interaction techniques for mobile devices. For example, understanding touch as a 3D finger orientation was the underlying concept of *Z-touch* by Takeoaka et al. [21] which used finger pitch angle as an input source, for controlling Bezier curves in a drawing application. Similarly, Kratz et al. [14] enabled 3D touch gesture detection by augmenting a tablet with a depth camera that captured the 3D space above the touchscreen. While *Z-touch* and the work by Kratz et al. [14] detect finger orientation using a vision-based sensing system, Rogers et al. [19] used a capacitive sensor array to detect the pitch and yaw of the finger. Zaliva [29] investigated detecting the finger orientation from the 2D contact point. Finally, Xiao et al. [28] used an off-the-shelf consumer touchscreen device to detect pitch and yaw gestures.

While the proposed additional input dimensions enrich the input possibilities, this 3D gesture design space causes ergonomic challenges. For example, Colley and Häkkilä [4] showed that pointing performance and gesture comfort of touch gestures vary with touch position and finger, whereby the lowest performance and comfort was found for the corners of the device, especially the top left one. The common direction from which a finger approaches the screen was found to be from the bottom right for one- and two-handed interaction of right-handed users [1]. However, Hoggan et al. [11], found that the feasibility of touch rotation depends on the rotation angle and input becomes harder when the hand rotation increases. Wolf et al. [26] further showed that the feasibility of pitch, yaw, drag, and finger lift gestures on hand-held devices depended on the grip and the touch location. They found

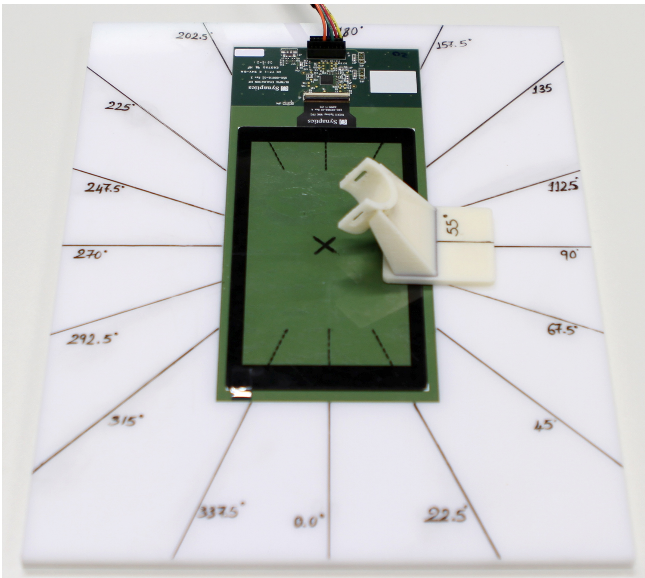


Figure 2. The study apparatus with the 3D printed 55° pitch stabilizer and the 16 yaw positions drawn on the touch surface.

that significant modifications from the natural grasp cause ergonomic problems, especially for one-handed interaction.

Le et al. [16] designers should concider ergonomic constraints when developing single-touch Back-of-Device (Bod) interaction techniques and therefore studies are needed to understand how users interact with devices. Beyond single-touch interactions, Lozano et al. [17] have shown that when designing new multitouch interaction techniques designers need to consider ergonomic factors. For example, Xiao et al. [28] identified additional ergonomic problems when using enriched touch input. Long fingernails made a large pitch unfeasible to perform. Xiao et al. [28] also restricted the yaw input to a range they "found comfortable to replicate in piloting", thus they covered one third of the full 360° yaw range in their study. To reduce ergonomic problems they proposed to rotate the finger and the mobile device simultaneously, thus reducing the angle the finger actually had to be rotated. In the presented work we systematically vary pitch and yaw to better understand the ergonomic constraints when using pitch and yaw as an input.

Overall, a body of recent work aims to extend the input space for touch interaction. A particularly active area aims to detect the 3D orientation of the finger that touches the screen and to use the pose as an additional input parameter. It is, however, unclear which finger orientations are actually feasible and ergonomic. To extend the existing body of research on 3D touch gestures, this paper investigates the ergonomics of approaching a touch point with different finger orientations. We show that the finger pitch and yaw angle have an effect on feasibility, while the finger yaw angles can be divided into *comfort* and *non-comfort* zones. Our work addresses the ergonomic constraints posed by human physiology on performing the touch action.

HYPOTHESES

Our study investigates the ergonomics of approaching a touch point with different finger orientations and is guided by the following three hypotheses:

Hypothesis 1 (**H1**): Even though users often use their non-dominant hand, e.g. in encumbered situations, users perceive touch actions performed with their dominant HAND as more feasible. Users prefer operating devices with their dominant hand, and we expected this influence our results.

Hypothesis 2 (**H2**): Changes in finger PITCH[3] would affect feasibility RATINGs. We decided to explore this hypothesis as past work provided little evidence on how pitch values affected input feasibility.

Hypothesis 3 (**H3**): The more the finger YAW[4] would diverge from the direction parallel to the user's arm, the lower the feasibility RATING would be. We noted that increased twist in the wrist was expected to decrease feasibility. While verifying this hypothesis, we endeavored to identify how much twist was allowed while still producing a feasibility RATING suitable for designing interaction techniques.

METHOD

In our study, we systematically manipulated the finger pitch and yaw while performing a touch action. To study our three hypotheses, we conducted the study in a controlled environment with a number of constraints to ensure the validity of the study. Our goal was to observe the touch action as an atomic task. Therefore, we artificially restricted the participants' finger posture to prevent them from subconsciously adjusting their hand, which would result in a larger input range. Moreover, movements of the participant's body would have caused a larger input range. Therefore, participants were not allowed to move either the apparatus or their chair.

To investigate the effect of finger orientation on the feasibility of a touch action, as an atomic task we explore the full potential input range. We used 4 pitch angles and 16 yaw angles, each with a step size of 22.5°.

Study Design

In a repeated measures experiment, we asked participants to perform touch actions with their index finger. We asked them to rate the feasibility of the touch action resulting in the dependent variable RATING. Feasibility, in this context, was defined as the effort required to perform the touch action. The experiment was conducted with three independent variables: PITCH and YAW of the index finger, as well as HAND. We used 10°, 32.5°, 55°, and 77.5° for PITCH. We did not investigate angles steeper than 77.5°, due to findings by Xiao et al. [28] who stated that a pitch of 90° cannot be detected and performed with long nails. For YAW, we covered the full 360° range

[3]In this paper, we define PITCH as the angle between the finger and the horizontal touch surface. PITCH is 0° when the finger is parallel to the touch surface, i.e. the entire finger touches the surface.

[4]In this paper, we define YAW as the angle between the finger and a mid-axis parallel the longer edge of the phone (when in horizontal mode). YAW is 0° when the finger is parallel to the long edge of the phone and increases when the finger is rotated counterclockwise.

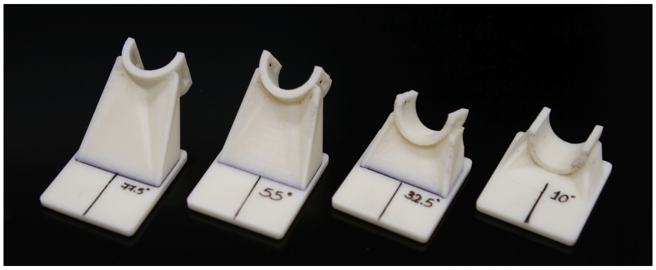


Figure 3. The four pitch stabilizers we used in the study to limit PITCH to 77.5°, 55°, 32.5° and 10° presented from left to right.

resulting in 0.0° to 337.5° with 22.5° steps. All combinations were tested with the index finger of the right and the left HAND. Thus, we used a PITCH $\times$ YAW $\times$ HAND $= 4 \times 16 \times 2$ study design resulting in 128 conditions.

Apparatus

Our apparatus design aimed to maximize the control over the independent variables. Xiao et al. [28] stated that it is difficult to reliably ensure that participants can touch a screen with a particular pitch. In their study, Xiao et al. used laser-cut plastic wedges to align the finger at a particular pitch. The wedges, however, were removed during the recording process, which influenced the accuracy. To ensure that participants perform the touch actions with a particular pitch, we used 3D-printed pitch stabilizers. We manufactured pitch stabilizers with a PITCH of 10°, 32.5°, 55°, and 77.5° as presented in Figure 3. Participants had to place the finger on the pitch stabilizer while performing a touch action. The four pitch stabilizers ensured that participants performed a touch action with a given pitch. Further, the pitch stabilizers ensured that participants did not vary the roll of the finger during touch acquisition.

We used a touch-sensitive sensor by Synaptics, to ensure that the participants touched the surface. The touch layer was surrounded by a white plastic frame to level the area around the touch layer (see Figure 2). This resulted in a flat surface that enabled secure positioning the pitch stabilizer on the sensor. We marked the center of the touch sensor with a permanent marker. We further marked the 16 input yaw angles with a line on the surface and wrote the angle next to the line (see Figure 4). The touch sensor was fixed on a desk to ensure that participants could not move it.

We employed a tablet to guide participants through the study. During the study, an application running on the tablet showed the hand, the pitch, and the yaw that should be used for the next trial. The application randomized the order of yaw and pitch. Participants were asked to rate the feasibility of the performed touch action with a slider control on a scale with 100 steps from '*easy*' to '*hard*'. Using continuous rating scales that have a long history in psychophysical measurement and enables a robust evaluation [22]. Further, we choose a slider with no ticks as Matejka et al. [18] showed that ticks influence the distribution of the results. Additionally, the application gave the opportunity to tick a checkbox indicating that the input was not feasible. The checkbox enabled distinguishing between very hard but possible and physically impossible touch actions.

Figure 4. The apparatus we used in our study, showing the tablet, the touch layer and one of the pitch stabilizer while one participant touches the touch surface.

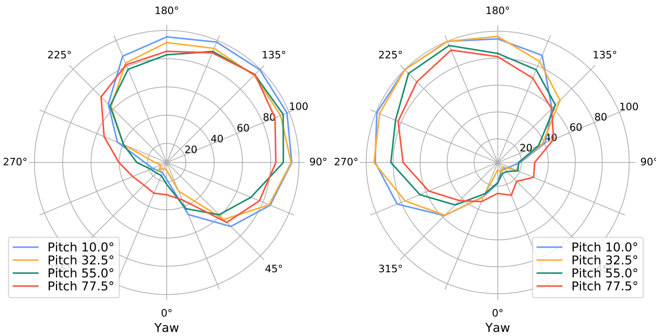
Participants

We recruited participants from an internal university self-volunteer pool. We invited all the volunteers to participate in the study. Of the volunteers, 9 female and 10 male participants agreed to take part in the study. These participants were between 22 and 44 years old ($M = 25.9$, $SD = 2.7$). Of all participants 16 participants were right-handed, 3 left-handed and none of the participants were ambidextrous. One of the right-handed participants did not follow the procedure of the study. Therefore, we discarded the data collected from this participant.

Procedure

After welcoming the participants, we explained the purpose and the procedure of the study. Afterwards, we asked them to fill a consent form and a demographics questionnaire. The participants were seated on a chair in front of the desk with the apparatus. The chair was aligned with the center of the apparatus. We fixed the position of the chair and asked participants to neither move the chair nor the touch layer of the apparatus during the study. We further explained to them how to place and use the pitch stabilizer. After the participants felt comfortable using the apparatus, we explained how to use the rating scale and the tick box, that is if they could not perform the touch action they should tick the box. Further, we explained that they should rate the effort required to perform the touch action and then explained the labels on the scale in detail. We explicitly mentioned that *easy* meant that little to no effort was required to perform that touch action whereas *hard* described an action that was near impossible to complete.

Next, we started the main part of the study. The tablet showed PITCH, YAW, and HAND that should be performed next. Participants were asked to perform the touch action in the center of the sensor (the center was marked as shown in Figure 2) three times using the given PITCH, YAW and HAND. We asked the participants to slide the finger in the guiding rail provided by the stabilizer. At the end of each condition, participants had to provide a feasibility RATING on the slider control on the tablet. Participants first performed the touch actions using all combinations of PITCH and YAW with one hand followed by the other hand, with the order of HAND being counter-balanced. Within HAND, the PITCH condition was randomized, and within the PITCH condition, the YAW condition was randomized to avoid



(a) Left hand rating (b) Right hand rating

Figure 5. The average feasibility RATING (from 0 = '*easy*' to 100 = '*hard*') for the different PITCH inputs.

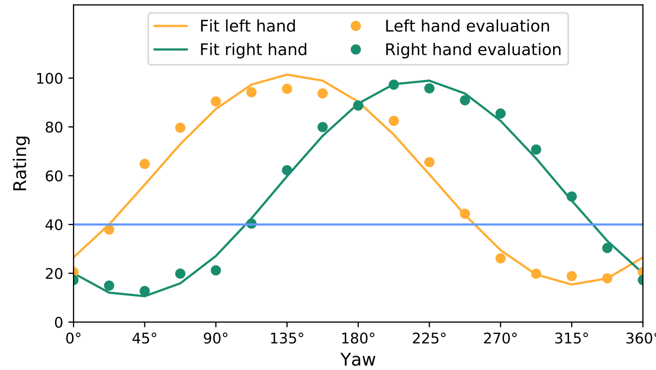


Figure 6. The average feasibility RATING (from 0 = '*easy*' to 100 = '*hard*') for the different YAW inputs averaged over all PITCHes. The figure also shows the fitted sin curve representing the RATINGs. The blue line indicates the threshold between *comfort* and *non-comfort* zones.

participants from changing the stabilizer often. After the participants had performed all conditions, we thanked them for their volunteer participation.

RESULTS

We collected 2304 ratings from 18 participants. Out of the 2304 rated conditions, 485 (21.1%) were marked by the participants as not feasible to perform. All inputs that the participants marked to be not feasible where considered to be *hard* (100 points) for the analysis.

We applied the Aligned Rank Transform (ART) [25] procedure to the feasible RATINGs, using the ARTool toolkit[5] to align and rank our data.

We conducted a three-way ANOVA to determine whether the independent variables significantly influenced the perceived feasibility of performing the touch action. Our analysis revealed significant main effects for PITCH, YAW, and HAND on feasibility ($F_{(3,2176)} = 5.413$, $p < .005$; $F_{(15,2176)} = 196.194$, $p < .001$.; $F_{(1,2176)} = 22.701$, $p < .001$, respectively). Further, we found significant two-way interactions between PITCH $\times$ HAND and YAW $\times$ HAND ($F_{(3,2176)} = 3.027$, $p = .028$; $F_{(15,2176)} = 147.566$, $p < .001$, respectively). However, there was no significant two-way interaction between PITCH $\times$ YAW ($F_{(45,2176)} = 1.179$, $p = .194$). Lastly, we found a significant three-way interaction between PITCH, YAW, and HAND ($F_{(45,2176)} = 2.361$, $p < .001$). Figure 5 presents the distribution of feasibility RATINGs for all YAWs and both HANDs. Consequently, we employed further comparisons to investigate how the different variables influenced the results.

[5] `depts.washington.edu/madlab/proj/art/index.html` last accessed: 05-17-2017

We calculated a Sine regression to predict the RATING based on YAW. We found a regression equation with $R^2 = .991$ for the right index finger and $R^2 = .978$ for the left index finger. The predicted RATING is equal to RATING $= 54.8 - 44.5 \sin(\text{YAW} + 0.9)$ for the right hand and RATING $= 58.4 - 43.1 \sin(\text{YAW} + 0.8)$ for the left hand with YAW in radians, see Figure 6.

Next, we investigated which YAW angles produced touch actions that are perceived as impossible to perform. For the right index finger, the participants stated 244 out of 1152 (21.2%) times that touch was not feasible using the given orientation and 241 out of 1152 (20.9%) times for the left index finger. For the right hand, 99.18% of trials that were perceived to be impossible fell into the range from 112.5° to 315.0°. In the case of the left hand, 100% of the impossible trials were reported in the range from 45.0° to 247.5°. Considering that the RATING is harder to perform in some input zones, we defined a threshold of 40 to mark the range where the trail was rated as impossible from the rest, as explained next. Consequently, we observed that the YAW space could be divided into two zones, which we named the *comfort* and *non-comfort* zones, as shown in Figure 7.

Further, we noted that for the right HAND, the *comfort* zone ($M = 51.89$, $SD = 36.65$) was rated significantly different from the *non-comfort* zone ($M = 62.95$, $SD = 36.29$) by conducting a Welch Two Sample t-test ($t(900.61) = -4.98$, $p < .001$). This was confirmed for the left hand (*comfort* zone: $M = 45.04$, $SD = 36.69$; *non-comfort* zone: $M = 60.92$, $SD = 38.91$) as well ($t(949.77) = -6.954$, $p < .001$). There-

Zone	HAND	df	F	p
comfort	right	3, 428	9.385	<.001
comfort	left	3, 428	9.436	<.001
non-comfort	right	3, 716	9.539	<.001
non-comfort	left	3, 716	6.049	<.001

Table 1. One-way repeated measures ANOVAs to determine if the RATING is depended on PITCH within zones and HAND.

Zone	HAND	df	F	p
comfort	right	5, 426	6.439	<.001
comfort	left	5, 426	8.505	<.001
non-comfort	right	9, 710	55.513	<.001
non-comfort	left	9, 710	49.397	<.001

Table 2. One-way repeated measures ANOVAs to determine if the RATING is depended on YAW within zones and HAND.

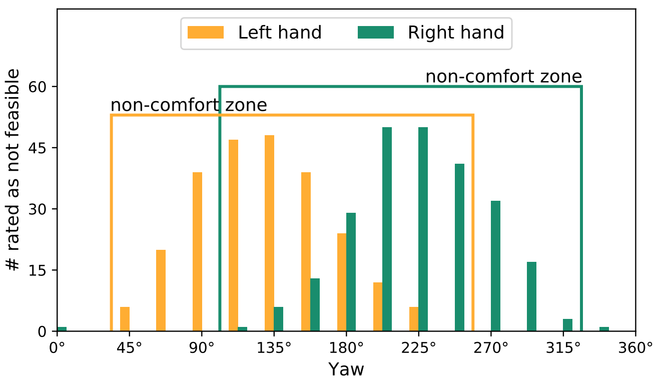


Figure 7. The bars represent how often a yaw angle was rated as not feasible to perform.

fore, we choose the threshold of 40 for the RATING to divide the two zones.

The *comfort* zone for the right HAND ranges from 326.25° to 101.25° and the *comfort* zone for the left HAND ranges from 258.75° to 33.75°. Therefore the span of both *comfort* zones is equal to 135.0° for both hands and two *comfort* zones overlap by 67.5° Thus the *non-comfort* zones are 225.0° wide.

We used four one-way repeated measures ANOVAs to investigate whether PITCH significantly affected the feasibility RATING in the two zones and HAND. As Table 1 shows, we found significant effects; the ratings are presented in Figure 5. Further, we did the same for YAW; and results are presented in Table 2.

Left-handed Participants

We also analyzed the data produced by the 3 left-handed participants. We collected 384 ratings from 3 left-handed participants. Out of the 384 ratings, 50 (13.0%) were rated not feasible. Figure 8 compares the average RATING for all YAW conditions between left- and right-handed participants. The data suggests that left-handed participants reported RATING similar to right-handed participants. Thus this indicates that the findings are valid irrespective of the dominant hand.

DISCUSSION

Our results show that finger orientation has a significant effect on perceived feasibility of touch actions. As expected, participants perceived actions performed with the dominant HAND as more feasible than those performed with the non-dominant hand. Thus, the result of the initial three-way ANOVA confirms **H1**.

Our analysis revealed a significant effect of PITCH on the feasibility RATING. This indicates that the feasibility of performing touch actions is influenced by finger PITCH confirming **H2**. This is in contrast to Wang and Ren [24] who found no difference in accuracy between vertical and oblique touch. Furthermore, the results indicate that flat angles are preferred when touching in the *comfort* zone while steep angles are overall rated to be easier when operating in the *non-comfort* zones.

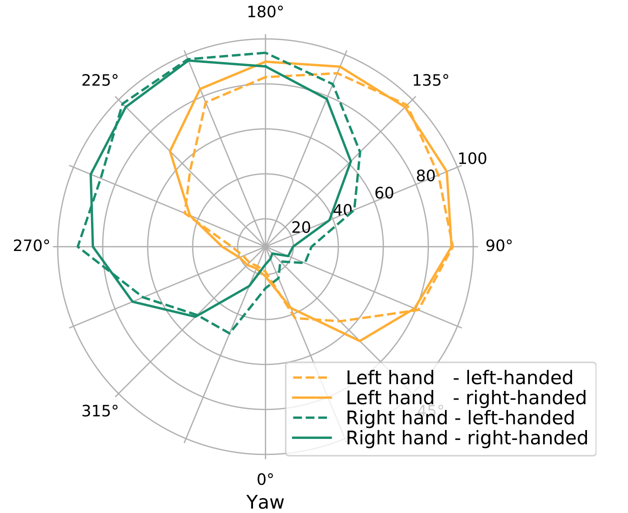


Figure 8. Comparison of HAND in respect to the handedness of the participants, showing the average value per YAW.

Owing to a significant requirement to twist the finger, higher ratings in *comfort* zone to otherwise are understandable.

Further, our analysis revealed a significant effect of YAW on the feasibility RATING. In particular, we found that the distribution of RATINGs can be approximated by a sine curve. This shows that the perceived feasibility of the touch action increases steeply while the finger diverts from the parallel-to-arm direction. We also observed that most YAW values could render the touch action impossible (as evidenced by the existence of *comfort* and *non-comfort* zones). Consequently, the range within which yaw input is feasible is highly restricted and a larger YAW results in decreased feasibility RATINGS which confirms **H3**.

Design Considerations

Here, we chart how our findings influence the design of future single-finger input techniques for interactive surfaces in the form of five design considerations.

Avoid entering the non-comfort yaw zone

The *non-comfort* zones cover 225° out of 360° of the possible input space for both hands and are therefore much larger than the *comfort* zones. The *comfort* and the *non-comfort* zones significantly differ in perceived feasibility when touching a surface with different finger orientations. Consequently, future designs of input techniques should not require the user to use orientations that fall into the *non-comfort* zones. Requiring input in the *non-comfort* zone creates a possibility for the task to be perceived as impossible. Thus, tasks like widgets that require rotating with a single finger should be avoided at all costs.

Range for effective yaw input depends on the hand

While many interactive surfaces can detect from which angle the user's hand is approaching, future designs must take that into account while designing yaw gestures. The yaw rotation possibilities depend on the hand used. If the interactive surface cannot detect which hand is being used, yaw gestures should be limited to the 45°-wide overlap in the *comfort* zones of the left and right hands to ensure that the gesture is feasible to perform with both hands.

Make use of pitch-based techniques for contextual features

We have shown that touch at different pitch angles is perceived as varying in feasibility. Previous work reported influence on accuracy. In contrast to yaw, the range of feasible pitch input is the same for the left and the right hand. This suggests that there is a design space for designing interactions based on finger pitch for interactive surfaces. Similarly to touch pressure techniques (e.g. Apple's 3D Touch), finger pitch could be used to activate additional functions such as contextual menus.

Make use of pitch-based techniques for modal interaction

As different pitch angles can be perceived and differentiated well, interacting at different finger pitch angles also affords different modes in touch-based reading devices like ebook readers and tablets. For example, pitch based techniques could offer an alternative mode (to time or pressure) when one needs to parse complex textual data. Most common techniques for parsing text include note-taking [8], annotating [9], and insight generation from these notes as a solo or collaborative activity [7]. Varying the pitch angles can activate the mode to highlight text, or annotate it with notes.

Use edges of the comfort zone for safety-critical input

Our results show that the perceived feasibility rating rises as the finger divert from the parallel-to-arm direction. Future designs could exploit this observation by using higher yaw angles for sensitive input. For example, when confirmation to restore factory settings is required, the user could be asked to perform a 67.5° yaw rotation. While the task would still fall in the *comfort* zone (and thus be feasible), it would require more effort than a single tap thus limiting possible slips.

A combination of pitch and yaw can also be used to offer a second dimension to afford sharing or disclosure. For example, sharing digital notes has been shown to improve performance in critical tasks [6, 27]. Setting the mode for digital notes to be private or transparent for public consumption could be done by varying pitch (simultaneously or in succession) with an angular yaw movement. Further work is required to address the opportunities and limitations resulting from this approach.

Explore the benefits of pitch when unsure about yaw

Our results show a potential for future designs to use pitch input when yaw values may fall outside of the *comfort* zone. This may be the case when multiple users use a single touch device e.g. when collaboratively browsing photos on a tablet lying on a table. Further, yaw is often limited when users are likely to use one-handed input e.g. while shopping. Given that appropriate sensing is available, pitch input may enable effective two-dimensional navigation even when the finger approaches the touch surface at a yaw angle outside of the *comfort* zone. Consequently, we suggest enabling pitch-based navigation in scenarios when yaw-based techniques are possibly restricted.

Limitations

The study used a highly controlled setting, which ensured that neither the participant nor the device was moved. Thus, our results can be directly applied in interactions only to stationary devices. Allowing the user to move the device or allowing the user to move around the device would increase the range of feasible inputs, but would increase the complexity of the interaction and the time required to interact. We, therefore, believe that it is advisable that users should not be required to interact in the *non-comfort* zone. However, as this paper is a first attempt to investigate the feasibility of a single touch action with varies pitch and yaw, the aim was to investigate the core limitations of using pitch and yaw as an input dimension.

Our study mainly focused on right-handed participants. A larger number of left-handed participants would be required for conducting statistical analysis of data from left-handed users. However, we assume that the *comfort* zone is similar for left- and for right-handed users. This is supported by the results of the three left-handed participants. While we cannot be certain that there are no differences, the similarity between left- and right-handed participants suggests that potential differences are small.

Our investigation is limited to pitch and yaw angles. We explicitly limited roll variation by using pitch stabilizers. Existing interaction techniques already use roll as an input source. For instance, in Apple's iOS, it is possible to roll the finger for precise text cursor manipulation. *Fat thumb* interaction by Boring et al. [2] used the pitch and the roll of the finger for pan and zoom operations. While the roll range is highly limited by the arm's kinematic chain, it still requires further investigation.

CONCLUSIONS & FUTURE WORK

We conducted a study to investigate the ergonomics of finger pitch and yaw as an additional touch input parameter. We asked participants to rate the perceived feasibility of performing touch actions with different finger orientations. We systematically manipulated the finger pitch and yaw while performing a touch action. We varied the input orientations using 4 different pitch and 16 different yaw angles. All combinations were performed with the index finger of the left and the right hand. The results show that not all orientations are equally feasible, with some orientations being infeasible to perform. Furthermore, we show that the input space for each hand can be divided into two zones; the *comfort* and *non-comfort* zones. Only 135° out of 360° of all yaw orientations are within the *comfort* zone and perceived as feasible. Based on our results we contribute six design considerations.

In this paper, device and participants remained at fixed positions which enabled us to identify the boundaries of human ability to perform pitch and yaw touch actions. While we investigated a static scenario, future work needs to explore the feasibility of different finger orientations when the device is held in the hands. This can be accomplished with smartphones which can track the hand while interacting with the smartphone, e.g. [15]. Furthermore, we are interested in further investigating potential differences between left-handed and right-handed users. In future work, we will aim to design new interaction techniques that make efficient use of pitch and yaw gestures. We hope that the considerations presented in this paper will inspire further developments in creating enhanced single-finger touch input interaction patterns.

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