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Biomechanics of Front- and Back-of-Tablet Pointing with Grasping Hands

Abstract

Considering the kinematic model of the hand allows for deeper understanding of target selection on the front and on the back of tablets. We found that the position where the thumb and fingers are naturally hovering when the device is held results in shortest target selection times.

We broaden our understanding of that ergonomic optimum by analyzing the touch data as well as 3D data. That allows us to model the entire hand pose including finger angles, thumb angles, and orientation.

We show how target acquisition with grasping hands is realized through bending the joints of the digits. For targets located very close to the palm of the grasping hand, the digit joints have to be bent till their limit, which is a less ergonomic motion that therefore requires longer selection times than pointing at targets with relaxed digits that are further away.

Introduction

With the rise of tablet devices, a new form factor of mobile devices is challenging interaction designers. Common ways to interact with handheld devices use the direct touch as input technique. Direct touch requires physical contact of the user's finger on the position of the physical content a user wants to interact with, e.g. touching an icon, while indirect touch techniques known from touchpads would allow for item selection without a physical digit touch. The common guidelines for mobile phone interaction – relying on direct touch – cannot directly be transferred to tablet devices as the different size and weight fundamentally change the requirements on ergonomic interaction design. A symmetric bimanual grip was recommended to be most appropriate (Oulasvirta et al., 2013) for enabling the ergonomic usage of tablet devices. Beyond common touchscreen interaction, that grip enables back-of-device interaction as proposed by Wigdor et al. (2007) through LucidTouch, a tablet-sized device.

Whereas, research on bi-manual tablet interaction (Wagner et al., 2012) and on back-of-tablet typewriting (Buschek et al., 2014) was been conducted, previous research did not address pointing on touchscreens of tablets nor through back-of-device interaction in depth. Consequently, corresponding design guidelines are not available. Thus, we explore both, pointing on touchscreens as well as on touchpads built in the back of the device.

To fully understand of how touch interaction on tablets works, we attached inertia sensors to the hand that allows us to record a 3D hand model while users interact with the device. The gained 3D information enriches the expressiveness of experimental data and allows us to gather information about hand configuration and orientation in addition to established data, such as touch contact on interactive surfaces. In a controlled experiment that setup is used to investigate target selection times from an ergonomic point of view: We explore what target positions that best accessible and use the 3D hand model to explain why some positions are easier to access while others are harder to reach.

Related Work

If a user holds the device while pointing, the hand has to solve multiple tasks and direct pointing becomes more challenging due to the hand's bio-mechanics. Thus, in addition to occlusion (Siek et al., 2007), a second problem of direct touch is the accessibility of targets that are further away or very close. The center of the tablet is hard to reach if the device is held in landscape format with both hands (Odell and Chandrasekaran, 2012). Moreover, for one-handed pointing on mobile phones it was found that the thumb performance varies with its posture (Trudeau et al., 2012). Poorest pointing performances results from excessive thumb flexion. When tapping on targets closest to the base of the thumb in the bottom right corner of the screen the performance is low. The highest performance is achieved when the thumb is in a rested posture, neither significantly flexed nor fully extended.

The device's form factor and resulting grip of phones and tablets are different. Therefore, we cannot directly transfer knowledge about ergonomics in phone touchscreen interaction to tablet's touchscreen and back-of-tablet interaction. Furthermore, whereas, back-of-device interaction has been shown to allow for extending the design space for hand-held devices (Wigdor et al., 2007) and others (Holman et al., 2012; Karlson and Bederson, 2007; Wobbrock et al., 2008) investigated one-handed phone interaction with grasping hands; no research (to the authors' best knowledge) exists that investigates how usable tablet interaction with grasping hands is.

We think that it is mandatory for proposing design guidelines for tablet touchscreen and back-of-device interaction to understand biomechanics of the hand. Thus the question addressed here is if tablet pointing performance depends on the digits' configurations of the grasping hand.

Method

Pointing and target selection at both, the touchscreen and a touchpad on the back of a tablet while the device is held with two hands has to the author's best knowledge not been investigated thus far. This defines a research gap that will be addressed in the following experiment.

Design

This study was designed as 2x2x2 within-subjects design with the independent variables *hand* (left and right hand), *augmentation* (with and without augmenting the participants' hands with motion sensors), and device side (whether pointing is executed on the front or on the back side of the device). The dependent variables were target selection time, error rate, hand orientation as well as the rotation angles for each joint of the digit that is used for pointing. For touchscreen pointing this is the thumb; and for back-of-device pointing, the index finger was used. The joints of the thumb have 5 degrees of freedom (DOF) as the lowest joint (TBJ) has three DOF and both upper joints (TMCP, TDIP) have just 1 DOF each (as shown in Figure 1). The two upper joints of the index finger (PIP, DIP) have also 1 DOF each. Its lowest joint (MCP) has just 2 DOF. In the study volunteered 16 participants (5 female and 11 male participants, 28.4 year in average (SD=4.8) from 15 to 46 years, 14 right- and 2 left-handed).

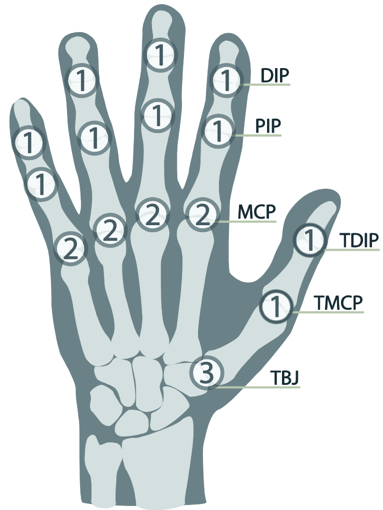

Figure 1: Human hand with joint names and degrees of freedom (DOF) per digit. The hand root has 3 DOF, the thumb has 5 DOF, 3 at the bottom joint (thumb basal joint: TBJ), 1 at the middle (thumb metacarpophalangeal joint: TMCP) and 1 at the top joint (thumb distal interphalangeal joint: TDIP), and the index finger has 4 DOF, 2 at the bottom (metacarpophalangeal joint: MCP), 1 at the middle (proximal interphalangeal joint: PIP), and 1 at the top joint (distal interphalangeal joint: DIP).

Task

The task was to select dark gray targets with grasping hands that held a tablet in landscape format with a bimanual symmetric grip. Participants selected targets in the same manner under all 8 conditions: with and without sensory augmentation, with each hand, and on both device sides. Each selection task begun by pressing a start button, positioned at X=64px (11mm), Y=374px (63mm) for the left-handed and at X=1216px (206mm), Y=374px (63mm) for the right-hand condition. Please note that all pixel and mm measures in this chapter are always counted from the left upper corner of the screen; and that the frame, which is not included in the mm-measurements has a height of 20mm and a width of 26mm. During the frontscreen conditions, the button was accessible through touching the frontscreen; for the back-of-device conditions a touchpad on the rear was used to select the start button. The targets appeared after the start button was released in random order 5 times per target size equally distributed over the tablet screen on a 7x10 grid (as shown in Figure 2). The targets were sized 28px/5mm, 42px/7mm, and 56px/10mm inspired by Parhi et al. (2006) and Hasan et al. (2012) and with the intention to represent the size of typical tablet content, such as text and buttons. Due to the limited access of targets at the left side of the screen for the right hand and of targets on the right hand side of the screen for the left hand, the targets for each hand were displayed on the 6 of 10 closest vertical grid lines. This overlap served to better understand target selection in the center area, which is hard to reach. The instruction for solving a task was to select the targets as quickly as possible.

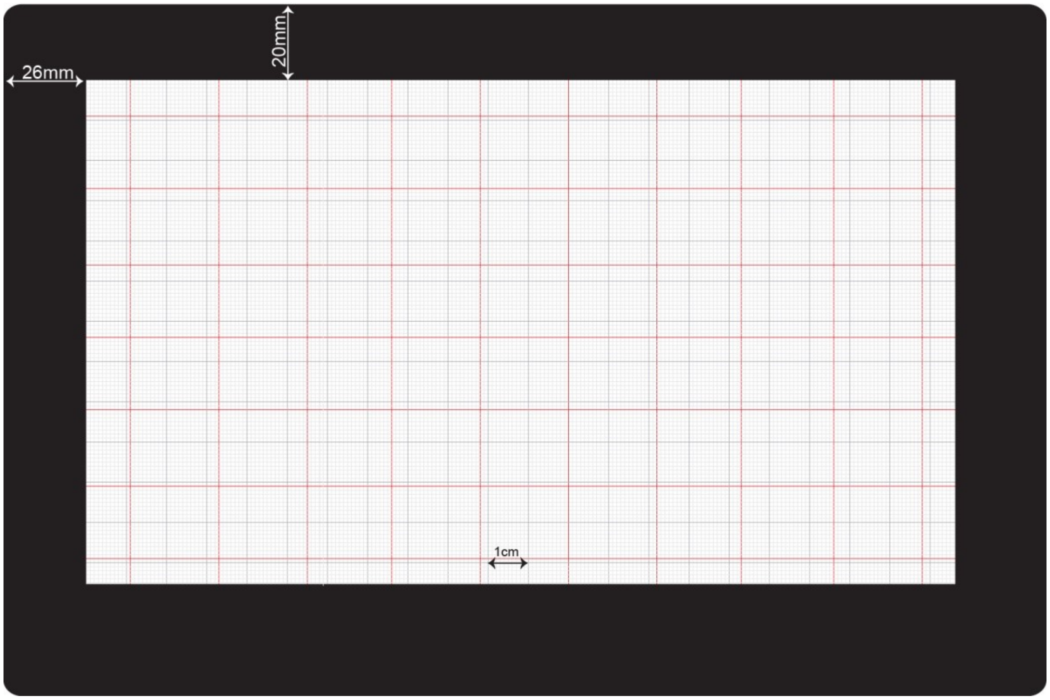

Figure 2: Apparatus: Tablet device including the 7x10 grid drawn in red where the targets occur.

Apparatus

Two apparatuses were employed in the experiment, as shown in Figure 3. Apparatus 1 was a tablet sandwich to present the experimental task and to record 2D data. Apparatus 1 consisted of two tablet devices glued together by their rear sides and connected via Bluetooth (inspired by Shen et. al., 2009). This allowed for sensing touch events on the back of the apparatus and to update the GUI of the device at the front accordingly. The size of the screen was 1280x742 pixels (without bottom menu bar) that are 21.7cm x 13.6cm.

Apparatus 2 is a system that records 3D data of the hand consisting of four wearable sensor sticks (multiplexed Magnetic Angular Rate Gravity (MARG) sensors that contain 3 degree-of-freedom (DOF) acceleration sensors (ADXL345) and 3 DOF magnetometers (HMC5883L) in combination with 3 DOF gyroscopes (ITG3200) for joint orientation tracking), a micro controller (Arduino Nano V3) and a PC running 3D hand model recording software. This approach was inspired by Kawano et al. (2007) who were using accelerometers, gyroscopes and magnetometers for analyzing 3D knee kinematics for estimating all knee joint angles, flexion/extension, and internal/external rotation. Kawano et al. (2007) evaluated the estimated angles numerically by comparing the results with an optical motion system. In the experiment presented here, an inertia sensor-based 3D tracking system was favored against optical motion systems, such as Vicon. Optical systems are great for tracking free-hand mid-air gestures, but may cause occlusion problems by the held tablet device.

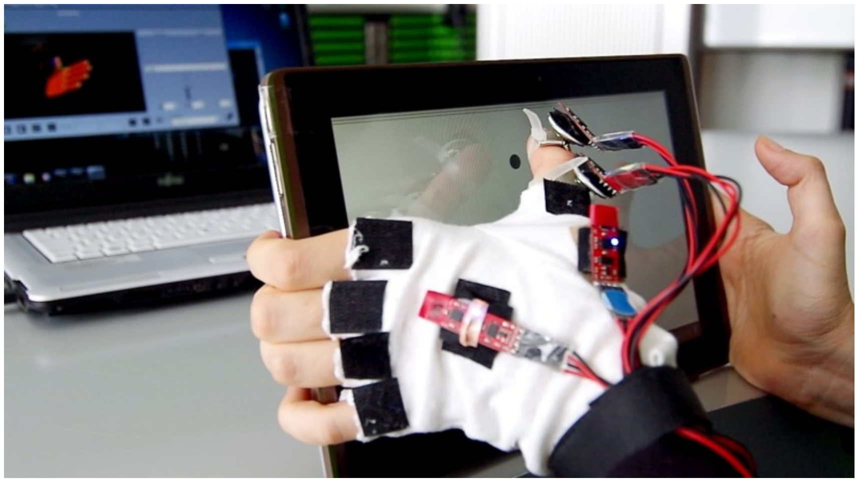

Figure 3: Real-time whole hand modeling using 9 DOF digit-mounted motion sensors allows recording a dynamic hand model while studying touch-based interaction.

The 3D hand model recording software used here is capable of tracking the configuration of single finger joints at over 30Hz in real time. To do this, a Java-based PC-Application fuses the raw sensor data from the accelerometer, gyroscope, and magnetometer. While recording, one sensor stick is always attached to the back of the hand and serves as a reference orientation for the whole hand. The reference is used to calculate the digit orientation relative to the hand root.

Three sensor sticks are mounted at each individual segment of the thumb or the index finger (depending on the condition) using rings and a shortened glove to keep the thumb- and fingertips uncovered and avoid touch recognition problems on the tablet's touchscreen. The sensors are attached to the joints through Velcro that allows for rapid switching between augmenting the thumb for the front conditions and the index finger for the back-of-device conditions during the experiment. The software of Apparatus 2 models the orientation of the entire hand as well as the configuration of every digit (thumb or index finger) segment that results in the whole digit pose.

Inertia sensors are known to cause drift problems. In the hand model, a drift of joint rotations is corrected using the Mahony (Mahony et al., 2008) and Madwig (Madgwick et al, 2010) filters that fuse the data of all three sensors and corrects the rotation drift of the gyroscope. The gyroscope data is used for detecting how much each digit joint is rotated compared to their neighbor joint and the hand root. Drift can influence the angles recorded with the tool, which would add noise to the joint angle data. Thus, before the experiment, the hand model recording software was tested through drawing angles of 30°, 45°, and 60° on paper and bending exemplarily the two upper joints of the thump (TDIP, TMCP, see Figure 6.1) according drawn angles 40 times per angle (30°/45°) as well as the two upper joints of the index finger (DIP, PIP) according drawn angles (45°/60°). Repeated measurement ANOVAs show that the maximum joint rotation angles did not differ significantly from angles drawn on paper ($F_{1,279}$=1.088, p=.767). This evaluation ensured that the angles recorded with the hand model software are about the same as the actual angle of the joints.

Both apparatuses, the tablet sandwich and the hand model recording software, are able to record logfiles. To synchronize both logfiles, the tablet sends "event labeling" messages to the software on the PC via WiFi when the start button is pressed as well as when a target is hit.

Measurements

The interaction time and the 2D touch events for selecting each target were recorded in logfiles on the front tablet device. The raw data of four sensor sticks with 9 DOF motion data each as well as the absolute hand root orientation and the rotation angle of each thumb joint, which is the base of the real time hand model, were recorded by the 3D software. In summary, data of 80640 trials on the tablet as well as on the PC was recorded (16 participants x 2 hands x 2 augmentation conditions x 2 device sides x 3 target sizes x 42 target positions per condition and hand x 5 repeated presentations per target size at each position). Finally, participants answered questionnaires about their gender, age, and hand dominance.

Procedure

After explaining the task and a short training, the tasks were solved in counterbalanced order, which means that half of the participants were solving the pointing task with each hand first without augmentation and afterwards with having the sensors attached to their hands. The last eight participants solved the task at first with and then without augmentation. Within these conditions, device side and hand was counterbalanced as well. While front-of-device interaction sensors were attached to the thumb; and during back-of-device interaction, the index finger wore sensors. One sensor unit was for both, front- and back-of-device interaction, attached to the back of one's hand. At the end, the participants filled in a demographic questionnaire.

Results

The analysis of the data recorded in logfiles on the tablet were structures by the following questions:

Q1: Do the performance measurements require different treatment for each *hand,* in accordance with the handedness of the participant or in regard the *side of the tablet* (front versus back) on those the pointing gesture is placed?

Q2: As a lack of influence of wearing the sensory *augmentation* on the objective performance measurements would permit considering all data for performance analysis, it was questioned if the hand's augmentation affects the 2D results.

Q3: As only trials were considered where the target was hit with the first touch, the other trials were defined as error and excluded from the data set. For calculating the *error rate*, the question is: how many targets per hand and target size were not selected on the first try?

Q4: After filtering the data in regard to ***Q1, Q2,*** and ***Q3***, the question is: How does the *target size* effect the target selection time?

Q5: The 2D data is analyzed to determine if the *target position* affects the target selection time?

Q6: Finally, the 3D data is analyzed to determine if target selection performance decreases if the hand pose, especially the rotation of the joints is less ergonomic?

Q1: Handedness

Repeated measure ANOVAs using a 5% significance level indicated that selecting a target was significantly faster with the *dominant hand* ($F_{1,46894175}$=14.776, p<0.001, $mean_{dominant}$=1096ms, $mean_{non\text{-}dominant}$=1148ms).

Because of the significant influence of the dominant hand on the target selection time, in the further results the factor *hand* was differentiated between dominant and none-dominant (instead of right and left). Thus, for any analysis that includes absolute target positions, just the data sets from the 14 right-handed participants will be considered. The data sets of both left-handed participants will be ignored as two data sets are too few to allow for quantitative analysis.

Q1: Hand

Repeated measure ANOVAs showed that for the right handed participants selecting a target was significantly faster with the *right hand* than with the left ($F_{1,5.325e+7}$=44.013, p<0.001, $mean_{right}$=1077ms, $mean_{non-dominant}$=1151ms).

Because of the significant influence of the hand on target selection time, and as targets in the center areas were selected with both hands in separate conditions; for further analysis on the influence of target position on target selection time, the calculations will be made with subsets of the data for each hand separately.

Q1: Device Side

Whether targets were selected on the front or on the back of the device affected the target selection time significantly ($F_{1,1.685e+09}$=531.073, p>0.001). Targets were selected in average about 1.7 times faster on the front of the device compared to the rear ($mean_{front}$=837ms, $mean_{rear}$=1420ms) that is shown in Figure 4.

Q2: Augmentation

Wearing the inertia sensors during the target selection task did neither slow down the interaction (*augmentation:* $F_{1,3985492}$=1.256, p=0.262, $mean_{standard}$=1051ms, $mean_{augmented}$=1179ms), nor increased the error rate ($errorRate_{standard}$=17.8%, $errorRate_{augmented}$=16.0%). Thus, wearing additional sensors had not significantly influenced target selection performance. Therefore, for further analysis the complete data, including both the sets recorded while the participants' hands were augmented and those while no sensors were worn, can be considered. Moreover, no interactions between *augmentation**device side* ($F_{1,7059085}$=2.224, p=0.136) and *augmentation*dominating hand* ($F_{1,323917}$=1.102, p=0.749) influenced the target *selection time* significantly.

Q3: Error Rate

When comparing the error rates per target location, only the data from the right-handed participants was considered. Pointing at targets on the touchscreen (front side) with the left hand caused an *error rate* of 14.4% (target size of 28px/5mm: 20.1%, of 42px/7mm: 13.6%, of 56px/10mm: 8.9%); and using the right hand resulted in an *error rate* of 12.9% (target size of 28px/5mm: 18.9%, of 42px/7mm: 12.0%, of 56px/10mm: 7.8%).

Pointing at targets on the rear caused a 13.1% *error rate* (target size of 28px: 13.8%, of 42px: 13.3%, of 56px: 12.1%) using the left hand and a 17.1% *error rate* (target size of 28px: 19.0%, of 42px: 17.7%, of 56px: 14.1%) when the right hand was used.

Please note that for all 2D performance analysis (target size, target position), the error trials were excluded and only trials where the target was selected by the first touch event after pressing the start button were considered.

Q4: Target Size

Repeated measure ANOVAs with *target size, device side*, and *dominant hand* as independent and target *selection time* as dependent factor yielded a significant effect of *target size* ($F_{1,28373387}$=28.295, p<0.001) as well as an interaction effect of *target size*device side* ($F_{1,17619152}$=17.570, p<0.001) on the target selection performance.

Repeated measure ANOVAs with two subsets of the data, one per *device side*, showed that target selection time differed not significantly between the three *target sizes* for selecting targets at the *front side* ($F_{1,394825}$=1.404, p=0.525) but for selecting at the *rear side* ($F_{1,45597714}$=44.332, p<0.0015) as shown in Figure 6.4. Despite the high variance in target selection time between the participants, a Tukey post-hoc test with pairwise comparisons yielded significantly different selection times between all three *target sizes* for back-of-device target selection (28px/5mm vs. 42px/7mm: p=0.045, 42px/7mm vs. 56px/10mm: p<0.001, 28px/5mm vs. 56px/10mm: p<0.001; with the average times of $\text{mean}_{rear\_28px/5mm}$=1534ms, $\text{mean}_{rear\_42px/7mm}$=1418ms, and $\text{mean}_{rear\_56px/10mm}$=813ms, Figure 4).

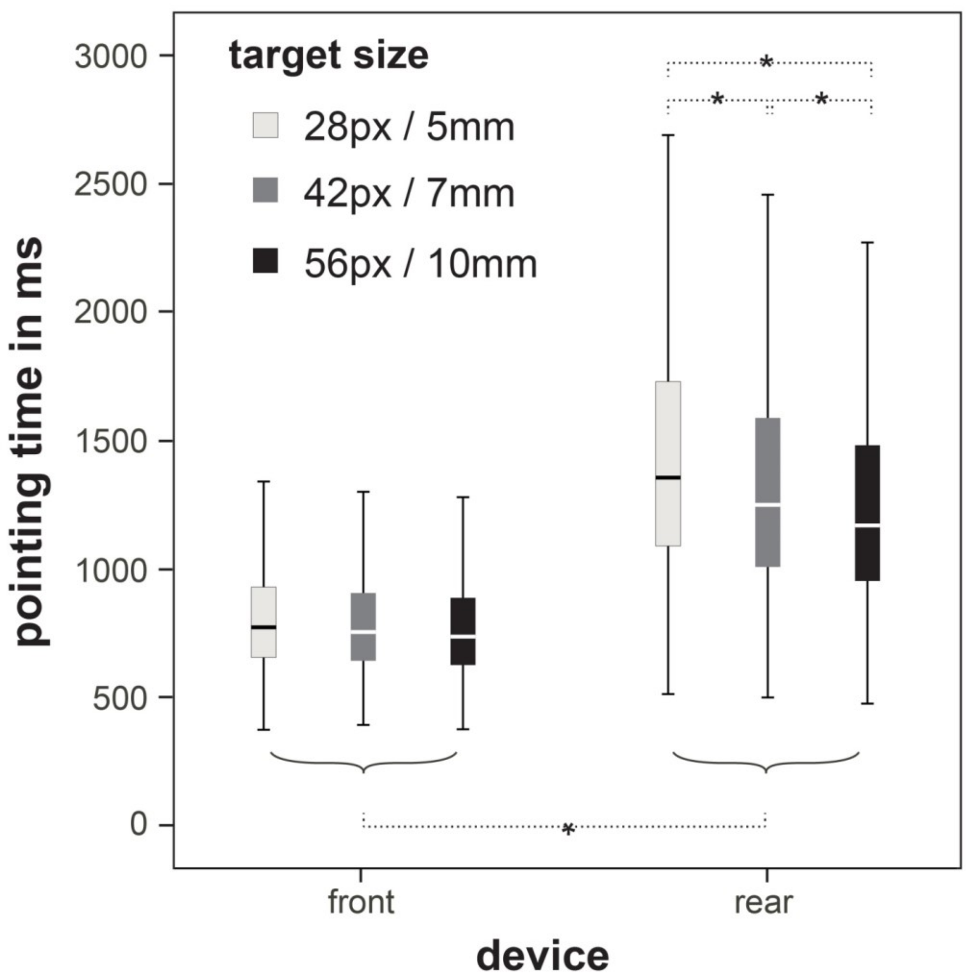

Figure 4: Boxplots: target selection time per target size on both the front and the rear of the device.

Q5: Target Position

Please note that (due to the influence of the hand's dominance on target selection time) the sub-set of right-handed participants were used for analysis of the influence of the target *position* on *selection time* as in this case it matters if the dominant hand is placed at the right or at the left device side.

Whereas, traditional pointing studies (following the setup of Fitts (1954)) are designed as 1-dimensional action; the pointing direction in this study had two, an x- and a y-dimension. Thus, the influence of the absolute (x-/y-coordinates) *target position* on target *selection time* is analyzed. Target positions refer to coordinates on the tablet counted from the upper left corner.

Handedness, hand, and device side influence target selection time significantly. Thus, for analyzing the influence of *target position* on *selection time*, repeated measurement ANOVAs were calculated with four sub-sets of the data, one set for each hand those were again split into sub-sets of both, touchscreen pointing released with the thumb and back-of-device pointing released with the index finger.

For touchscreen pointing (front) with the right hand (of right-handed participants), ANOVAs yielded a significant difference in target *selection time* depending on the horizontal x-position of the target ($F_{5,1.342e+6}$=3.194, p=0.018) but not regarding the vertical y-position ($F_{6,3.033e+6}$=1.351, p=0.909).

For touchscreen pointing (front) with the left hand (again of right-handed participants), ANOVAs indicated a significant difference in target *selection time* regarding both, the x-position ($F_{5,1.847e+7}$=2.576, p=0.025) as well as influenced by the y-position ($F_{6,3.033e+6}$=1.351, p=0.909).

For back-of-device pointing at touchpads (rear) with the right hand, ANOVAs showed that *selection time* is significantly influenced by the x-position of the target ($F_{5,3.059e+7}$=6.474, p<0.001) as well as by y-position ($F_{6,2.012e+7}$=3.530, p=0.002).

For back-of-device pointing at touchpads (rear) with the left hand, ANOVAs indicated a significant difference in target *selection time* regarding both, the x-position ($F_{5,4.531e+7}$=6.977, p<0.001) as well as dependence on the y-position ($F_{6,1.701e+7}$=2.171, p=0.043).

In summary, the x-position of a target significantly influenced the target selection time in all cases (selecting with right and left hand through pointing at a touchscreen as well as at a touchpad on the rear of the device); and the y-position always affected the target selection time significantly except when the left hand was used for pointing on a front sided touchscreen.

Whereas, no significant difference was found for the influence of y-position in target selection time when pointing with the left hand on the touchscreen (front); Tukey post-hoc tests indicated for this condition still a marginal faster pointing time for targets located in the lower vertical (486px/82mm counted from the upper edge) center than if the target is located on the top of the display (54px/9mm) as shown in Table 1. If using the right hand for pointing at targets on the touchscreen, both most outer positions, the top (54px/9mm) and the bottom (702px/119mm), take significantly longer than if targets were located closer to the vertical center. Whereas, pointing at targets on the back of the device that are located at top and bottom interaction areas is slower than for targets in center positions; the outer areas that take longer are larger (up to 162px/27mm and from 594px/101mm onwards counted from the top) for back-of-device pointing than for pointing at the front sided touchscreen.

Post-hoc comparisons using the Tukey test show that targets, located in the center (x-position), take significantly longer in acquisition than targets that are placed closer to the vertical frame edge where the hands are grasping the device (Table 2). If the targets are accessed from the front, the center area that required significant longer pointing time is slightly smaller (left hand: 580-709px/98-120mm, right hand: >=580px/98mm) than if targets are selected at the rear side where the area with worse pointing performance is larger (451-838px/76-142mm).

*Table 1: Post-hoc pairwise comparisons of target selection time in dependence on the target's y-position (Signif. codes: '***' <0.001, '**' <0.01, '*' <0.05, '.' <0.1 ').*

		Y POSITION						
		54	**162**	**270**	**378**	**486**	**594**	**702px**
	mm	**9**	**27**	**46**	**64**	**82**	**101**	**119mm**
FRONT					**left hand**			
	9		0.9448	0.8324	0.6380	0.0546 .	0.7716	0.999
	27	0.9448		0.9999	0.9937	0.4984	0.9996	0.991
	46	0.8324	0.9999		0.9997	0.7013	1.0000	0.947
	64	0.6380	0.9937	0.9997		0.9290	1.0000	0.817
	82	0.0546 .	0.4984	0.7013	0.9290		0.7717	0.127
	101	0.7716	0.9996	1.0000	1.0000	0.7717		0.914
	119	0.999	0.991	0.947	0.817	0.127	0.914	
					right hand			
	9		0.0021 **	< 0.001 ***	< 0.001 ***	< 0.001 ***	0.0583 .	0.5941
	27	0.0021 **		0.3514	0.8825	0.6372	0.9554	0.3236
	46	< 0.001 ***	0.3514		0.9877	0.9996	0.0325 *	< 0.001 ***
	64	< 0.001 ***	0.8825	0.9877		0.9998	0.3083	0.0183 *
	82	< 0.001 ***	0.6372	0.9996	0.9998		0.1093	0.0026 **
	101	0.0583 .	0.9554	0.0325 *	0.3083	0.1093		0.90956
	119	0.5941	0.3236	< 0.001 ***	0.0183 *	0.0026 **	0.90956	
BACK					**left hand**			
	9		0.2082	< 0.001 ***	< 0.001 ***	< 0.001 ***	0.7238	0.9979
	27	0.2082		0.02523 *	0.0873 .	0.2914	0.9793	0.05007 .
	46	< 0.001 ***	0.02523 *		0.9999	0.9618	0.0011 **	< 0.001 ***
	64	< 0.001 ***	0.0873 .	0.9999		0.9958	0.0065 **	< 0.001 ***
	82	< 0.001 ***	0.2914	0.9618	0.9958		0.0352 *	< 0.001 ***
	101	0.7238	0.9793	0.0011 **	0.0065 **	0.0352 *		0.3507
	119	0.9979	0.05007 .	< 0.001 ***	< 0.001 ***	< 0.001 ***	0.3507	
					right hand			
	9		0.1069	<0.001 ***	<0.001 ***	<0.001 ***	0.0203 *	0.0380 *
	27	0.1069		0.2100	0.0209 *	0.0256 *	0.9979	<0.001 ***
	46	<0.001 ***	0.2100		0.9589	0.9851	0.5288	<0.001 ***
	64	<0.001 ***	0.0209 *	0.9589		1.0000	0.0938 .	<0.001 ***
	82	<0.001 ***	0.0256 *	0.9851	1.0000		0.1175	<0.001 ***
	101	0.0203 *	0.9979	0.5288	0.0938 .	0.1175		<0.001 ***
	119	0.0380 *	<0.001 ***	<0.001 ***	<0.001 ***	<0.001 ***	<0.001 ***	

*Table 2: Post-hoc pairwise comparisons of selection time in dependence on the x-position (Signif. codes: '***' <0.001, '**' <0.01, '*' <0.05, '.' <0.1 ').*

		X POSITION									
		64	**193**	**322**	**451**	**580**	**709**	**838**	**967**	**1096**	**1225px**
	mm	**11**	**33**	**55**	**76**	**98**	**120**	**142**	**164**	**186**	**208mm**
FRONT		**left hand**									
	11		0.1984	0.9460	0.6905	< 0.001 ***	< 0.001 ***				
	33	0.1984		0.7067	0.0014 **	< 0.001 ***	< 0.001 ***				
	55	0.9460	0.7067		0.1408	< 0.001 ***	< 0.001 ***				
	76	0.6905	0.0014 **	0.14080		0.0278 *	< 0.001 ***				
	98	< 0.001 ***	< 0.001 ***	< 0.001 ***	0.0278 *		0.0085 **				
	120	< 0.001 ***	< 0.001 ***	< 0.001 ***	< 0.001 ***	0.0085 **					
						right hand					
	98						0.0053 **	0.0066 **	< 0.001 ***	< 0.001 ***	< 0.001 ***
	120					0.0053 **		1.0000	0.0967 .	0.2004	0.6919
	142					0.0066 **	1.0000		0.0860 .	0.1816	0.6623
	164					< 0.001 ***	0.0967 .	0.0860 .		0.9995	0.8993
	186					< 0.001 ***	0.2004	0.1816	0.9995		0.9769
	208					< 0.001 ***	0.6919	0.6623	0.8993	0.9769	
BACK		**left hand**									
	11		0.2108	0.9622	0.9910	0.0531	< 0.001 ***				
	33	0.2108		0.6736	0.0348 *	< 0.001 ***	< 0.001 ***				
	55	0.9622	0.6736		0.6733	0.0020 **	< 0.001 ***				
	76	0.9910	0.0348 *	0.6733		0.1863	< 0.001 ***				
	98	0.0531	< 0.001 ***	0.0020 **	0.1863		< 0.001 ***				
	120	< 0.001 ***	< 0.001 ***	< 0.001 ***	< 0.001 ***	< 0.001 ***					
						right hand					
	98						< 0.001 ***	< 0.001 ***	< 0.001 ***	< 0.001 ***	< 0.001 ***
	120					< 0.001 ***		0.4253	< 0.001 ***	< 0.001 ***	0.0860 .
	142					< 0.001 ***	0.4253		0.0249 *	0.0047 **	0.9543
	164					< 0.001 ***	< 0.001 ***	0.0249 *		0.9962	0.2952
	186					< 0.001 ***	< 0.001 ***	0.0047 **	0.9962		0.1076
	208					< 0.001 ***	0.0860 .	0.9543	0.2952	0.1076	

The pointing performance for each axis is shown in Figures 5 and 6. The pointing performance depending on 2D target position is visualized with a 3D plot of time over a 2D grid of target position as shown in Figures 7 and 8. Please note that for the overlapping regions (x-position: 98, 120mm from the left edge), the value from the dominant (right) hand is visualized, as these were smaller than interaction times when using the left hand. This approach is led by the suggestion that pointing with the dominant hand is easier and thus, that may be used for pointing at center areas.

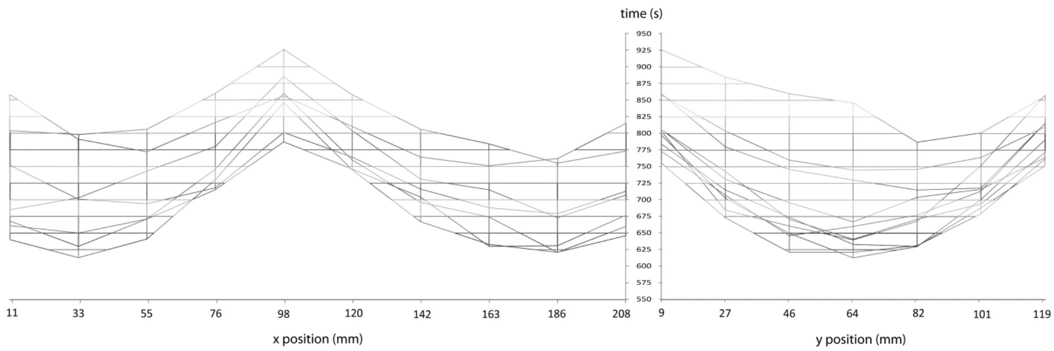

Figure 5: Pointing time per axes for front-of-device target acquisition.

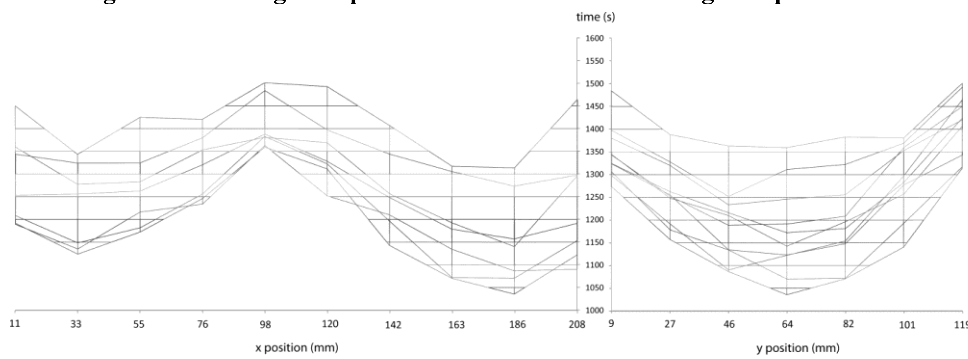

Figure 6: Pointing time per axis for back-of-device target acquisition.

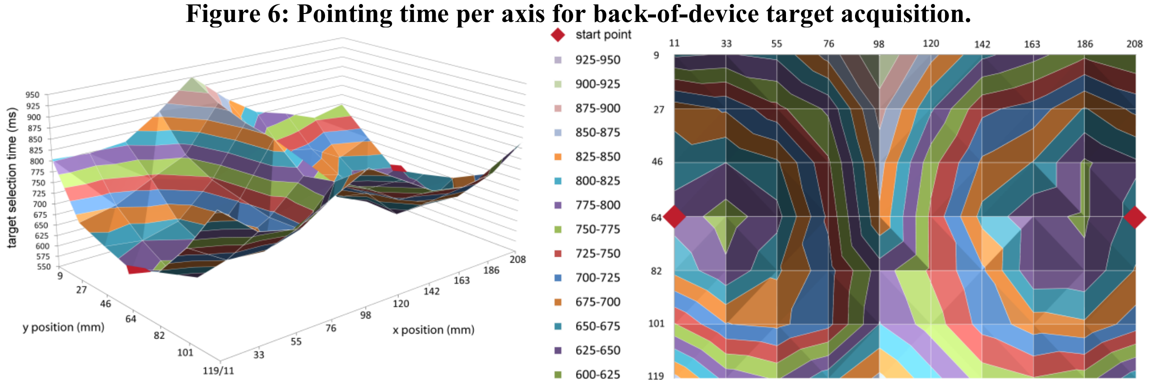

Figure 7: Pointing time for target acquisition at the front of a tablet. Left: time is represented as z-axis, right: time is represented as heatmap. The target positions are represented through the x- and y-axes. Target selection always started after touching the red square-shaped start point.

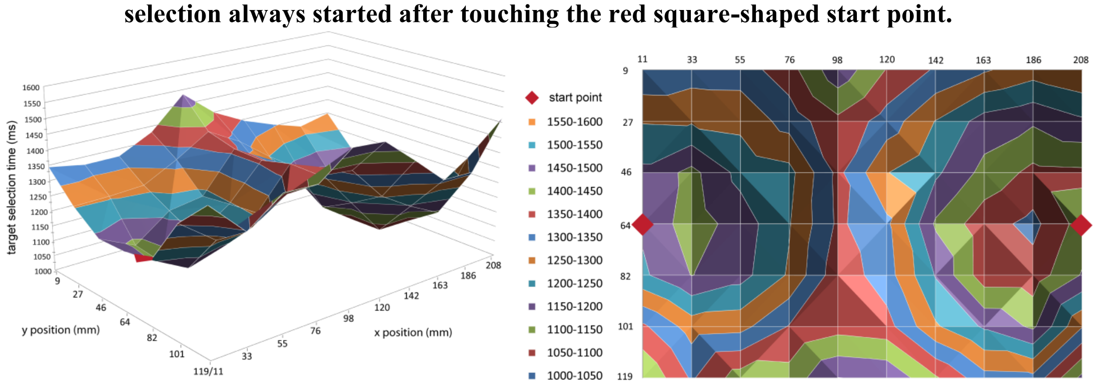

Figure 8: Pointing time for target acquisition at the back of a tablet. Left: time is represented as z-axis, right: time is represented as heatmap. The target positions are represented through the x- and y-axes. Target selection always started after touching the red square-shaped start point.

Figure 5 and Figure 6 visualize that the shortest *selection times* for pointing at both device sides are in the vertical center at the outer *x-positions* 33 and 186mm; and the longest *selection times* were at the vertical bottom and top at the central *x-positions* 98mm counted from the left side. Looking at *selection times* of targets in order of their vertical position shows that the outer positions take longest, while the center positions require the shortest *selection times*. These results are significant as shown in Table 1 and Table 2.

Plotting time in 3D over a target position grid (Figure 7, Figure 8) shows that target *selection times* plot in a third dimension over the target *x*- and *y-positions* forms a sink shape for each side accessed with one hand for both *device sides*.

The minimum of target selection time that is surprisingly not positioned closest to the start button but has an optimum at X=33/186mm, Y=64mm, whereby the start button is located at X=11/208mm, Y=64mm. From there, the selection time increases almost symmetrically for both hands (with slightly shorter times for the dominant hand); and has its maximum in the center of the device, which (in contrast to the position of the optimum) is suggested considering Fitts's Law (Fitts, 1954). In Fitts' Law, selection time increases over distance (in dependence of target size), which at least for the target positions close to the edges is not the case.

Q6: Joint rotation

For each target selection trial, data recording the hand movements was gathered. Furthermore, depending on the condition, data measuring the pose and the movements of the thumb for touchscreen pointing and of the index finger for back-of-device pointing was collected. The raw data of the hand model consists of a 3 DOF magnetometer attached to the hand root for modeling the absolute hand orientation and of one 3 DOF gyroscope attached to the hand root (labeled as *root* in Figure 9) as well as to each segment of the thumb (labeled as *TBJ* and *TMCP,* and *TDIP* in Figure 8 and explained in the caption of Figure 1) and to the index finger (labeled as *MCP* and *PIP,* and *DIP* in Figure 9). This data served to track hand and joint rotations for a dynamic model of the entire hand pose with the exact thumb and index finger configuration. The raw data for the hand root and each thumb and index finger segment in angle values (degrees) was translated and synchronized with the logfiles from the tablet apparatus using unique labels as described in the *measurements* section. Incomplete data sets were excluded; and just the data that represents trials where the target was successfully hit with the first touch was considered. Furthermore, the data from the left-handed participants was excluded as hand dominance had a significant influence on the task as shown above. Thus, 13491 data sets of target selection trials in total were considered for the analyses containing interaction times, 2D touch information as well as 3D hand pose and movement data.

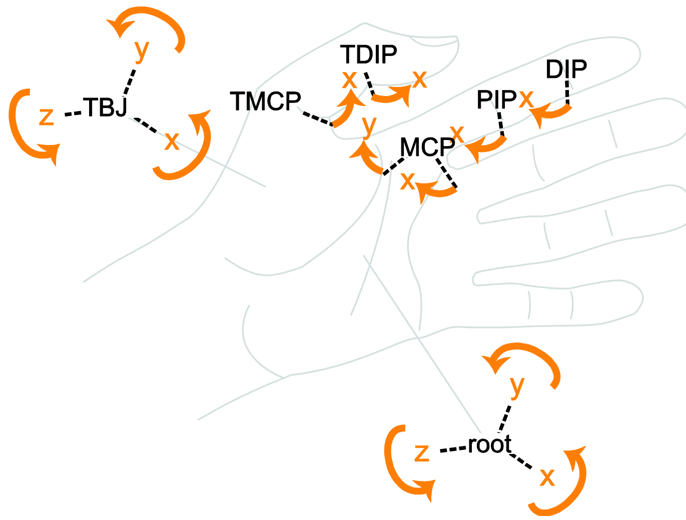

Figure 9: DOF of the hand model: the root of the hand model has 3 DOF; the DOF of the thumb and digit are similar to the motor DOF of the hand (Figure 6.1), which are 5 DOF for the thumb (3 at TBJ, 1 at TMCP, and 1 TDIP), and 4 DOF for the index finger (2 at MCP, 1 at PIP, and 1 at DIP). The x-/y-motions of the hand root match to position translations on a tablet when this is held like in Figure 3.

The aim of this analysis is to use the 3D data to help understand the findings gained through analyzing the 2D touch data. Through analyzing the 2D data it was shown that target selection time depends on the target position (*x-, y-position*). Analyzing the 3D data aims to provide a better understanding of why for example selecting very close targets (in dependence of the start position) takes longer than selecting targets that are slightly further away (especially in the x direction) as this is a contradiction to the established target selection model of Fitts' Law. It was assumed that for closer targets the joints may require to be rotated in an inconvenient way. To investigate the potential influence of joint rotation on pointing performance, the following joint and hand states were analyzed:

Joints rotation (*angle_max*)*:* The average maximum of joints rotations (relative to the joint that is nearer to the hand root or to the hand root itself) for each target position and over all participants while pointing a target. This data is used to investigate if a joint is stressed through a rotation that reaches the biomechanical limit of the joint.

Joint motion (*angle_range*): The amount of joint motions that is calculated as average difference between the maximum and the minimum joint rotation angle per target position across all participants while pointing a target. This data is used to analyze the amount of motion required to select a target, which is interpreted as physical effort.

Touchscreen Position

Through ANOVAs it was investigated if a joint of the thumb (labeled in Figure 8 as *TBJ, TMCP,* and *TDIP*) moves significantly more (measured as *angle_range*) while pointing at certain x- and y-positions on the touchscreen. Further ANOVAs were conducted to test if selecting targets on certain x- or y-positions on the tablet's touchscreen influenced the amount a joint is rotated (*angle_max*).

For both hands, the *x-position* affects the entire amount of motion that the bottom thumbs joint (*TBJ*) are executing around their y-axes (*TBJ range_y* of the left hand: $F_{5,2983}$=2.636 p=0.021, Turkey post-hoc test: X=33mm and X=76mm: p=0.027 as shown in Figure 10 (1); and

TBJ range_y of the right hand: $F_{5,4273}$=4.953 p>0.001; Tukey: X=98mm vs. X=186mm: p=0.009, X=98mm vs. X=208mm: p=0.002, X=142mm vs. X=186mm: p=0.044, and X=142mm vs. X=208mm: p=0.012, see Figure 10 (2). ANOVAs indicated that the x-position affects the rotation of the bottom joint corresponding to the rotation around the x-axis *(max_x* at *TBJ:* $F_{5,4273}$=2.216 p=0.05; Tukey: 142mm vs. 186mm: p=0.039, see Figure 10 (3)). Finally, the x-position also affects the maximal rotation angle of the bottom joint in rotation around the y-axis *(max_y* at *TBJ:* $F_{5,4273}$=4.203 p>0.001; Tukey: 98mm vs. 186mm: p=0.007; 98mm vs. 208mm: p=0.008, see Figure 10 (4)).

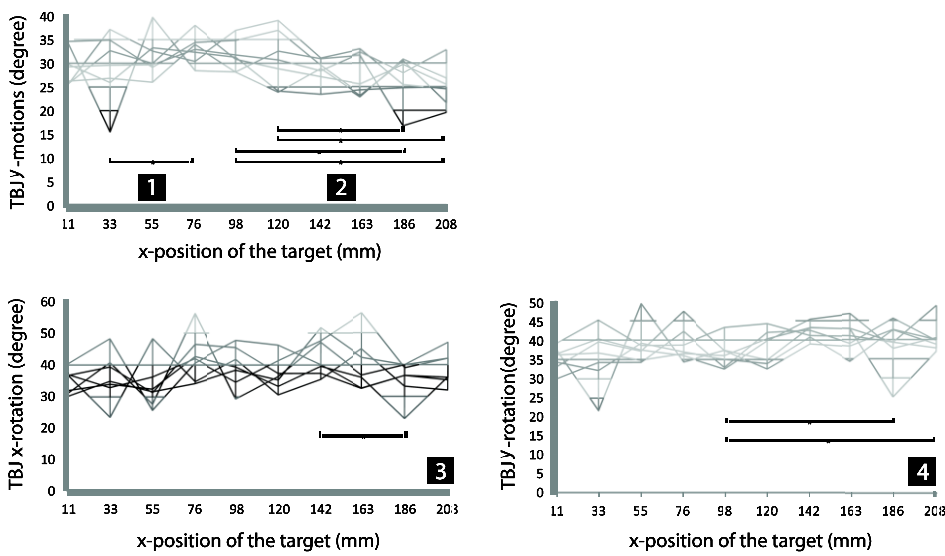

Figure 10: Significant different (*) thumb motions and maximal joint rotation per x-position of selected targets.

In summary, the greatest influence of target position on joint angles was indicated for the bottom joint (TBJ) of the right hand. In general, the thumb was moved less and bended less at the x-positions that required least target selection time (X=33/186mm counted from the left edge). Motions are shown in Figure 10 (1) and 10 (2); and joint rotation is presented in Figure 10 (3) and 10 (4)

Back-of-Device Pointing

Similar to pointing performance on the front sided touchscreen, ANOVAs were conducted for analyzing back-of-device pointing. The motion of the index finger joints (*DIP, PIP*, and *MCP*, Figure 9) while pointing at certain x- and y-positions on the back of the device was measured as *range_x*. The amount each joint was rotated most while selecting a target was recorded as *max_x*.

The average of maximal joint rotation (*max_x*) of the index finger while pointing at different target positions on the back of the device differed significantly for the right hand for motions around the x-axis of the middle joint (*PIP*) when pointing at different x-positions ($F_{5,2681}$=2.410 p=0.025); but no significant result was found in a post-hoc Tukey test (p>0.05).

Figure 10 shows the maximal rotation angle for the x- and y-positions. Whereas, no significant difference was found in dependence of the x- or y-position; the diagram shows that the joint is rotated most at the vertical center (Y=64mm) of the outer x-positions (X=11/208mm). These positions (which this 3D analysis was aimed to better understand) require longer selection times than the ones that are located a bit further in the center (X=33/186mm).

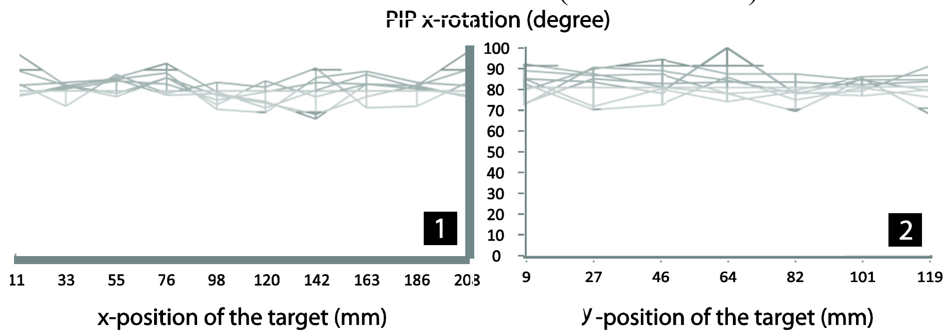

Figure 11: Motions (1) and maximal joint rotation (2) of the index finger per x-position of selected targets.

Discussion

Discussion of the 2D Results

The presented results are in line with Odell and Chandrasekaran (2012) who defined regions close to the vertical edge of a hand-held tablet easy to touch. Moreover, the presented results show that similar areas are well accessible for back-of-device interaction. In contrast to Odell and Chandrasekaran (2012), here detailed analyses are provided on the selection time in dependence on target position.

Despite the high variance in target selection time between the participants, significant effects of target size on target selection times were found. In contrast to expected selection times, this experiment shows that very short horizontal distances from the edges require surprisingly more time for selections than targets slightly further away. An optimal position for each device side is indicated by the presented data, which leads to shorter selection times than positions closer to the start button.

One reason for unexpected long target acquisition close to the edge where the hand is placed could be that the hand is occluding the target and thus, it takes longer to be seen. For example, targets may appear underneath the thumb. As the phenomenon of longer pointing times for targets that are very close by located to the hand occurs also for back-of-device pointing, this argument can be excluded as pointing at the rear does not cause occlusion problems (Baudisch and Chu, 2009).

Because the hand's biomechanics influence its feasibility (Hrabia et al., 2013; Vardy, 1998), the presented results provoke the assumption that biomechanic capabilities and limitations of the hand are the reason for the shorter interaction times at the optimal positions versus closer target positions. A suggestion may be that if the joints of the thumb and index finger are bended significantly to reach targets close to the edge (11/208mm); the joint rotation limitation may be reached. Thus, the selection time may increase due to increasing physical effort compared to when targets are touched that are located slightly further away (33/186mm from the display's vertical edges). A similar finding was provided by Trudeau et al. (2012) for one-handed interaction with mobile phones. Through tracking the thumb and wrist poses with an optical motion system it was shown that motor performance in target acquisition was greatest when the thumb was in a typical resting posture, neither significantly flexed nor fully extended.

Discussion of the 3D Results

Although, the tendency that the area very close to the start button requires more manual effort than the optimal target position cannot be shown through significance tests, this phenomenon that we found through analyzing the 2D data becomes visible by descriptive diagrams that show the effort and maximal rotation per joint over the x- and y-position of the device, as shown in Figure 10 and Figure 11.

The data of the kinematic hand model was analyzed to explain the unexpected longer selection times of targets that are located very close to the vertical device edges compared to those a bit further away. It was suggested that very close targets may need more time than those a bit further away as the digit that is selecting that target may need to rotate its angles up to the limit that is possible which may result in worse performance. Moreover, the amount of movement were analyzed as pointing time is expected to increase with larger distance (Fitts, 1954); and larger distance requires more movements.

Joints allow rotations up to different maximal angles, as shown in Figure 12. The assumption of the previous analysis is that pointing takes longer if the target position requires a digit to be bent in a way that stresses its joints by approaching the rotation limit. The rotation limits of the thumb joints are, according to Vardy (1998) and Hrabia et al. (2013), *max_x*=90° for the *TDIPI* joint, *max_x*=85° for the *TMCP* joint as well as *max_x*=110°, *max_y*=70°, and *max_z*=90° for the *TBJ* joint.

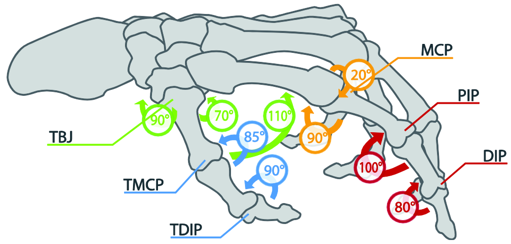

Figure 12: Maximal joint rotation of digit joints.

Even though the maximal rotation angles per x- and y-positions do not differ significantly for back-of-device pointing; it has been shows that for the very outer positions (X=11/208mm, Figure 11) the index finger has to be bent to its biomechanical limitation of about 100 degrees, which is shown in Figure 12. Thus, it has been shown that the index finger's middle (*PIP*) joint is rotated until its limit at those target positions that take longer than targets a bit further away. This is a novel finding related to tablet interaction as usually a Fitts' Law like approach would predict shorter selection times for targets closer to the start position.

Whereas, the joint rotation of the thumb does not reach an angle that is close to the limit (Figure 10); again targets that are a bit further away than the positions close to the edge require fewer rotations of the *TBJ* joint. Furthermore, the physical effort measured in amount of motions is less for these targets (X=33/186mm) than for the closer ones (X=11/208mm).

One may question why the center regions do not show any difference to the other positions as these were indicated to take longest when analyzing the 2D data (Figures 5-8). For reaching the center areas the entire hand had to be moved as digit motions alone cannot access the center of a tablet. The shift from relying rather on digit movements for closer target selection toward moving the whole hand for targets that are further away refers to the kinematic chain model (McCarthy, 1990).

In summary, the rotation maximum as well as the amount of motion during target acquisition is influenced significantly through the target position, whereby the thumb shows significantly different movements and configurations in the bottom joint regarding the x- and y-axis of this joint, but never for the z-axis. The effects of the target position on the kinematic model of the thumb were shown to be significant between the center and outermost positions; while the index finger show the tendency to be bent most when targeting very close to the edge.

Thus, the finding of the 2D data is that targets at the optimal position can be selected faster than closer ones; it could not be shown through ANOVAs. But this effect is also not large within the 2D data, and the differences between the outer and the center positions are equally well visible in both the 2D as well as in the 3D data. Therefore, as done with the 2D data, the characteristics of the optimal target position is visualized by diagrams plotting the average maximal rotated joint angles as well as amount of motion over the x-positions at the device, as shown in Figure 10 and Figure 11. While the joints have to move more for touchscreen pointing or are stressed at the outer x-positions for back-of-device pointing, an optimal position about 59mm from the vertical frame edges and 84mm from the upper device edge (including the frame) could be indicated to be the ergonomically optimum. For touchscreen interaction, this corresponds to the position where the thumb is roughly hovering when holding the device relaxed, as shown in Figure 13. For back-of-device interaction, the fingers are placed roughly there to hold the device.

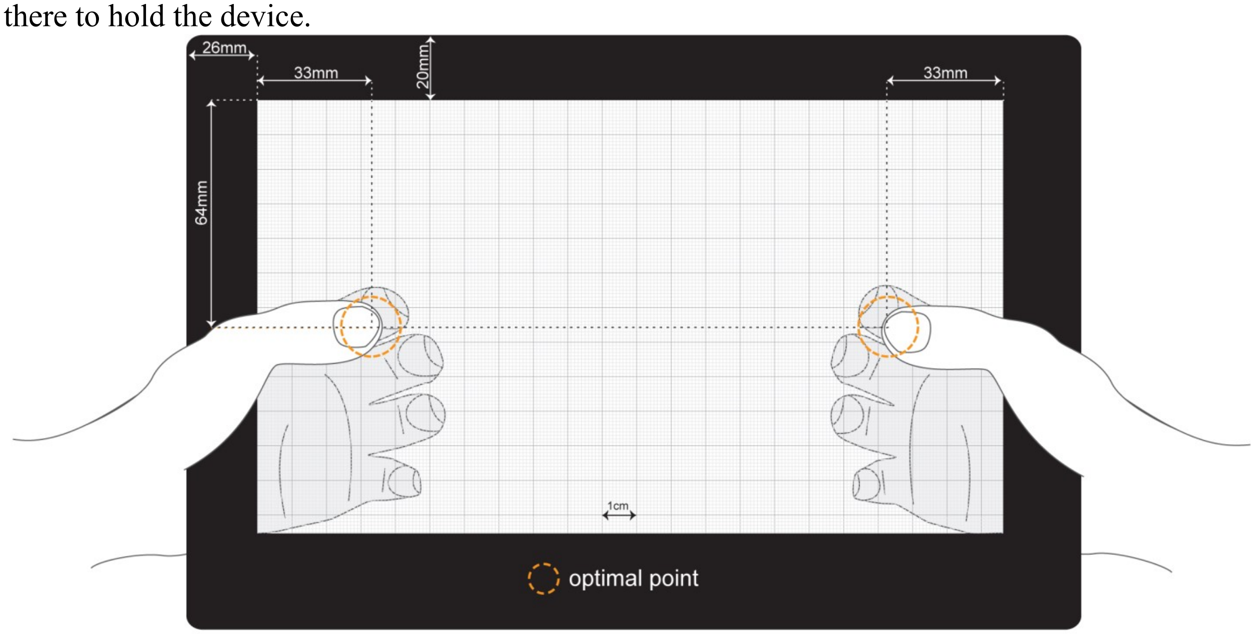

Figure 13: The areas where the thumb (or for back-of-device interaction the fingers) hovering are predestinated for touch-based interaction. These are ergonomic optimal points that require the least target selection time.

Whereas, these findings are similar to one-handed thumb interaction, where the thumb performs best when it is not flexed nor fully extended, but in a relaxed position (Park and Han, 2010; Trudeau et al., 2012); this experiment showed that a similar phenomenon was found for the index finger for back-of-device interaction. Furthermore, the two-handed grip allows relaxing one hand quite a bit for accessing the middle of the tablet, as shown in Figure 7 and Figure 8. Accessing these areas would not be possible for one-handed interactions and it does not even stress the joints significantly, as the entire angle motion does not increase dramatically (Figure 10 and Figure 11). This can be explained by the kinematic chain model (McCarthy, 1990), which assumes that the next joint, which is the wrist, makes more motor work when the digits reach their limit. This phenomenon does not occur in one-handed phone interaction and is thus a true contribution in understanding ergonomics in pointing with the hand that holds a tablet. Thus, due to the two-handed grasp when holding a tablet in the proposed way, the access area of a hand-held device increases for interactions that are performed with the grasping hand.

Design Guidelines

In the following part, conclusions are drawn that propose design guidelines for pointing on both tablet sides while holding it with two hands. Whereas, Trudeau et al. (2012) proposed to place widgets at locations that are well reachable with the thumb; here guidelines are recommended that do not constrain the interaction area to well accessible locations but rather aim to address the challenge of pointing targets at the entire surface on the front and on the back of the device. Furthermore, the ergonomically optimal point for direct touch pointing at the location where the digits naturally are while holding the device will be the base for the guidelines.

Considering ergonomic optimal points: Locations where the digits are hovering while holding the device are recommended to place GUI components controlled by direct touch. On average these optimal points are located at about 59mm from the vertical frame edge and 84mm from the upper device edge (including the frame). Users' hands differ in size and the device grasp differ between users and also between situations for the same user. Thus, a dynamic definition of the ergonomic optimal point may be appropriate when placing icons and widgets in the layout.

Pointing techniques: If it is desired to reach the entire tablet surface on the front and on the back of the device, direct touch has several ergonomic shortcomings. Targets that are further away from the area where the hands are holding the device are hard to reach directly. Moreover, areas that are very close to the edge that is grasped are inconvenient to point at. Thus, indirect touch (relative pointing) should be used instead of direct touch for pointing. Combining the ergonomically optimal point with a relative pointing technique allows overcoming the shortcomings of the direct touch technique for distance pointing on touch-sensitive surfaces.

Dynamic GUI components: Components should be re-thought in order to utilize the good reachability at the vertically outer sides. For instance, virtual keyboards should be vertically split into two parts for two-handed tablet interaction, whereby the right part is displayed where the right hand is grasping the device and the left part where the left hand is holding it. With that guideline, an empirical evidence for a hybrid keyboard design that combines both, the dynamic to the grasp re-adjusting *iGrasp* keyboard (Cheng et al., 2013) and the split keyboard of Oulasvirta et al. (2013) is provided.

Conclusion

This article describes work towards considering hand posture and articulation in target acquisition tasks using the thumb for touchscreen pointing and the index finger for back-of-device pointing with tablets. Design features of mobile computing technology such as device size and key location may affect thumb motor performance in touchscreen performance as well as the index finger performance for back-of-device interaction when the device is held with both hands. Empirical observations on biomechanical factors affecting target acquisition performance are made using a contact-based tracking apparatus as well as a hand model glove in a target acquisition task. This allowed observations on biomechanical effects on user performance. Ergonomic optimal points for touch-locations are identified for each hand that grips the device and for both device sides. Finally, pointing design guidelines are formulated that rely on ergonomic optimal points to overcome the shortcomings of the direct touch technique for distance pointing on touch-sensitive surfaces that are grasped, such as tablets that are held with both hands.

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