Biomechanics of Thumb Touch Gestures on Handheld Devices

Philipp Tiefenbacher
Institute for Human-Machine Communication, Technische Universität München
philipp.tiefenbacher@tum.de

Amir Chouchane
Institute for Human-Machine Communication, Technische Universität München
amir.chouchane@tum.de

Daniel Merget
Institute for Human-Machine Communication, Technische Universität München
daniel.merget@tum.de

Simon Schenk
Institute for Human-Machine Communication, Technische Universität München
simon.schenk@tum.de

Gerhard Rigoll
Institute for Human-Machine Communication, Technische Universität München
rigoll@tum.de

CHI'16 Extended Abstracts, May 7–12, 2016, San Jose, CA, USA.
ACM 978-1-4503-4082-3/16/05.
http://dx.doi.org/10.1145/2851581.2892294

Abstract
Touch interaction has reached high popularity due to the widespread use of handheld devices. Nowadays, devices with screen sizes above 8" are not uncommon. Grasping such big handheld devices needs two hands to feel comfortable. Consequently, only the two thumbs are available for touch gestures. This work analyzes the biochmechanics of thumb touch interactions. In two scenarios, 18 participants perform single-thumb and dual-thumb sliding gestures. The first scenario incorporates no time constraints while the second does. The results reveal differences in the gesture characteristics between dominant and non-dominant thumb input as well as between single-thumb and dual-thumb input. These findings motivate the necessity of a dynamic thumb interaction model.

Author Keywords
Functional model; touchscreen; mobile; thumb; study

ACM Classification Keywords
H.5.m [Information Interfaces and Presentation (e.g. HCI)]: Miscellaneous

Introduction
Direct touch interaction with one hand can be uncomfortable and tiresome for users [12, 15], especially when performing gestures on big handheld devices. On such de-

vices, it is often convenient to hold the device in landscape mode with both hands. Here, only the thumbs are available for interactions. That is why we focus on thumb interaction.

Two-handed touch interactions have been widely studied [11, 17]. Kin et al. [10] and Tiefenbacher et al. [15] discovered differences between single-handed and two-handed multi-touch interactions. Recent works [4] aimed at detecting the hand pose based on the touch points to enhance the gesture recognition. We advance this idea by stating that after the recognition, a mapping function should also consider dynamic hand characteristics, e.g., number of interacting thumbs.

The hand has 27 degrees of freedom (DOF) [5]. The thumb is independent from the other fingers and has 5 DOF. It consists of the interphalangeal (IP), metacarpophalangeal (MCP) and the first carpometacarpal (CMC) joint. The IP joint between the distal and proximal phalanges enables flexion and extension (1 DOF). Both joints, MCP and the first CPC, allow for flexion and extension (2 DOF) as well as abduction and adduction (2 DOF). The MCP joint is located between the proximal phalanx and metacarpal, while the first CPC joint is between the metacarpal and trapezium.

Based on this anatomy of the thumb as well as the neuroscientific aspects (handedness [14] and synchronicity [13]), we expect deviations in the characteristics of the individual gestures. Considering gesture characteristics is of interest in order to find an adequate functional mapping of gesture features, e.g., speed, to a certain value. We think that such a mapping function should consider human biomechanics to enhance the task performance and the ease of use. For the goal of creating a dynamic thumb interaction model, we recorded and evaluated the gesture speed and size of the thumbs in a study.

Related Work

Ullen et al. [16] discovered that the thumb tapping force and accuracy depend on the gestures phase characteristic. In-phase gestures revealed a higher force and accuracy than the corresponding anti-phase gestures. Furthermore, the spatial distribution of the dominant hand was more regular than for the non-dominant hand. This study solely focused on a tapping gesture. We want to evaluate thumb performance of sliding gestures. For gestures on a touch screen, the force can (often) not be measured, thus we only record the gesture speed and size.

Hook and Standley [7] found differences in the force of thumb to index finger pinch grips. The force was higher with the remaining fingers being flexed instead of extended. Furthermore, a huge difference between non-dominant and dominant thumb force was found. These results raise the question whether the speed and size of single-thumb and dual-thumb gestures are affected.

Bergstrom and Oulasvirta [2] presented a comprehensive model of the thumb's interaction region on handheld devices. They solely concentrated on the interaction region and did not consider dynamic features as the speed. Furthermore, evaluating a handedness effect was not the scope of their work.

Hypotheses

Our goal is to reveal biomechanical differences of thumb touch gestures. The joints of the thumb (IP, MCP, CMC) have different ranges of motion. For instance, the maximum range of the first CMC is $56°$, while the IP range is $73°$ [8]. The ranges of motion determine the possible shapes of touch gestures. That is why we investigate differences in gesture size and speed between the motion axes (horizontal and vertical). Moreover, the joint orientations vary, which

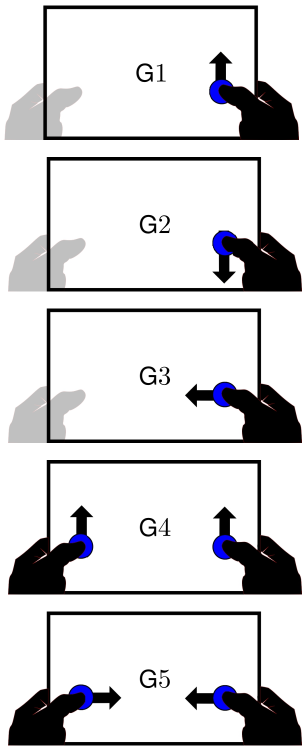

Figure 1: Gestures one to five of the study.

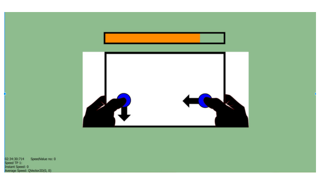

Figure 2: The graphical user interface during S2.

may have an impact on the motion direction (up- and downward).

It is commonly known that the dominant hand has more strength than the non-dominant hand [1, 9]. This fact may also be true for dual-thumb gestures, leading to differences in the gesture speed or size between non-dominant and dominant thumb.

Sensorimotor synchronization (SMS) is commonly measured in the form of finger tapping gestures [13], although SMS happens in many contexts. For instance, it is known that hand gestures synchronize with speech [3]. The parallel activity of both thumbs during a touch gesture may consequently lead to a synchronicity between the thumbs.

In summary, we outline the following hypotheses:

H1 The gesture speed and size differ according to motion axis and direction.
H2 The gesture speed and size of the dominant thumb are larger than those of the non-dominant thumb.
H3 The gesture speed and size of the dominant thumb are lower for dual-thumb gestures than for single-thumb gestures.

Figure 1 depicts all gestures performed during the study. The users execute the first three gestures (G1 to G3) with their dominant thumb in order to evaluate axis and direction characteristics (H1). For measuring H2, both thumbs perform the same motion simultaneously as shown in Figure 1 (G4 and G5). For the evaluation of H3, the dominant thumb moves in the same direction, but either a single-thumb gesture is performed (G1 and G3) or the second, non-dominant thumb follows the motion of the dominant thumb (G4 and G5). If there is no synchronicity effect for thumb interactions, the dominant thumb motion has to be similar between the single-thumb and dual-thumb gestures.

User Study

The study comprised 18 (6 female) participants which conducted two different scenarios on a Microsoft Surface Pro 2. This handheld device has a screen size of 11.6” with a resolution of 1920x1080, which corresponds to 208 dpi. We measured the thumb length between the first CCP joint and the tip of the dominant hand. The average thumb length of our participants was 116.1 mm. All participants stated to be right-handed. The participants were grasping the device with both hands in landscape mode while standing upright.

In the first scenario (S1), we imposed neither a performance requirement nor a time constraint on the participants. Each of the five gestures had to be performed ten times in a randomized order. Afterwards in scenario two (S2), the participants should fill a progress bar by performing the gestures as fast as possible. Here, each gesture had to be repeated 80 times to finish a progress bar. The repetitions enable the users to focus on maximum performance. No thinking about the kind of gesture is necessary. The scenarios are not compared with each other due to these differences in the setup. After finishing one gesture in S2, we asked the participants to evaluate it via the NASA R-TLX [6] questionnaire.

The graphical user interface was kept as simple as possible. Participants faced a big image of the gesture that should be mimicked. Figure 2 depicts the interface of S2 with the additional progress bar. The gestures were not recognized during the experiment but in a post-processing step. Moreover, we removed gestures with a duration below 50 ms and an euclidean distance below 1 cm. This assures that a thumb tapping is not classified as a certain gesture. Based on these thresholds, 32 of 900 gestures in S1 and 626 of 7200 gestures in S2 were removed. We averaged the remaining unbalanced samples of each user for S1 and

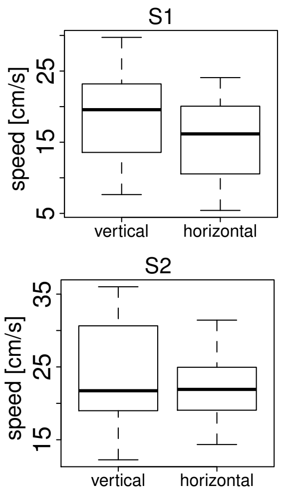

Figure 3: Speed of the dominant thumb for a vertical and horizontal motion.

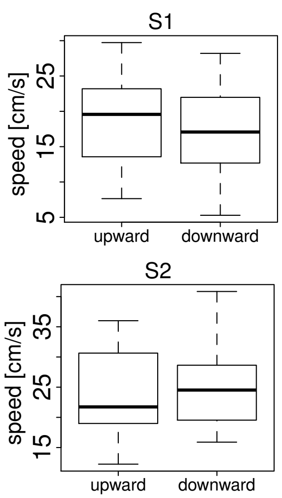

Figure 4: Speed of the dominant thumb for an up- and downward motion.

S2 separately. This way we received a balanced design with 18 measures per gesture per scenario.

We calculate the speed and the size of the thumb gestures via the euclidean distance of the x and y samples at 100 Hz. Speed and size are important features of a gesture, since both are necessary for ascertaining a functional mapping. The gesture size allows to determine the range of a mapping function, while the gesture speed reveals the slope (precision) of the function. For instance, users might perform a gesture more slowly when they want to be precise.

Results

We check the data for normality with the Shapiro-Wilk test. Based on the outcome, we either perform a paired student t-test or a paired Wilcoxon signed-rank test. All tests are conducted with a significance level of $\alpha = .05$.

H1: Single-thumb gesture characteristics differ according to motion axis and direction
For assessment of motion axis performance, the dominant thumb performs a vertical (G1) and a horizontal (G3) sliding gesture.

Gesture Speed The data of the thumb speeds exhibits normality (p_{S1}=$.89$, p_{S2}=$.90$). A paired student t-test reveals significance for S1 (t(17)=4.126, p<0.001), however, the gesture speed in S2 does not differ (t(17)=1.085, p=$.29$). Figure 3 illustrates that the average vertical thumb speed is 19.16 cm/s (SD=6.74 cm/s), while the horizontal thumb speed is 15.51 cm/s (SD=5.75 cm/s) in S1. This contrast in speed does not exists in S2 with 23.84 cm/s (SD=7.16 cm/s) and 22.12 cm/s (SD=4.22 cm/s) for vertical and horizontal thumb motion, respectively.

We analyze the influence of the motion direction via a vertical up (G1 as before) and down (G2) sliding gesture. The data is normally distributed (p_{S1}=$.71$, p_{S2}=$.75$). The speed differs in S1 (t(17)=3.108, p=0.006), while S2 does not differ ((t(17)=-0.673, p=0.51)). Figure 4 reveals downward speed of 16.57 cm/s (SD=6.46 cm/s) in S1. In S2, the downward speeds 24.79 cm/s (SD=7.08 cm/s), respectively. The upward gesture speeds (G1) are as in the former comparison.

Gesture Size The size of the dominant thumb gestures G1 and G3 are normally distributed (p_{S1}=$.47$, p_{S2}=$.25$). The t-test discovers a difference in distance for S1 (t(17)=3.857, p=$.001$) but not for S2 (t(17)=0.788, p=$.0.44$). In S1, the average size is 3.65 cm (SD=1.41 cm) vertically and 3.08 cm (SD=1.00 cm) horizontally. The gesture sizes shorten in S2 to 2.50 cm (SD=1.26 cm) and 2.33 cm (SD=0.65 cm) for a vertical and horizontal motion, respectively.

The analysis of the motion direction based on the gestures G1 and G2 shows only a normal distribution for S1 (p_{S1}=$.94$, p_{S2}<$.001$). Changes in the gesture size can neither be observed for S1 (t(17)=0.835, p=$.42$) nor S2 (V=61, p=$.30$).

H2: Gesture speed and size are larger for the dominant thumb than for the non-dominant thumb
For comparing the non-dominant with the dominant thumb, we evaluate speed and size of the thumbs for gestures G4 and G5.

Gesture Speed Normality is given for both scenarios (p_{S1}=$.11$, p_{S2}=$.94$). The t-test discovers a difference in speed for S1 (t(35)=-5.71, p<$.001$) as well as for S2 (t(35)=8.76, p<$.001$). Figure 5 illustrates the speeds of the thumbs. The average speeds in S1 were 12.51 cm/s (SD=6.46 cm/s) and 14.75 cm/s (SD=6.68 cm/s) for the non- and dominant thumb, respectively. In S2, the thumb speeds were 13.28 cm/s (SD_{non}=4.43 cm/s) and 19.66 cm/s (SD_{dom}=5.32 cm/s).

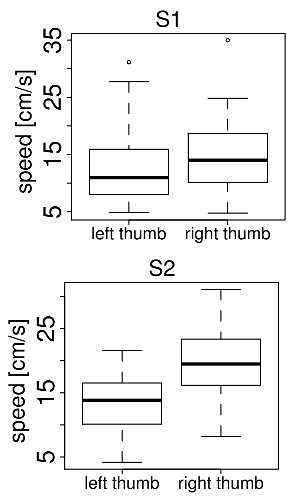

Figure 5: Speed of the left thumb and the right thumb, when performing the same gesture in parallel.

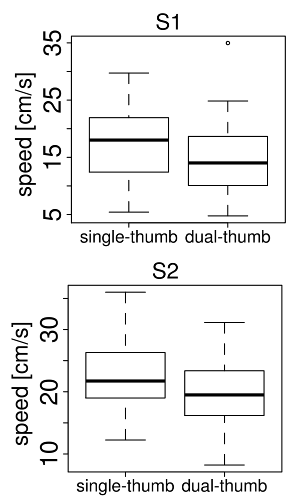

Figure 6: Speed of the dominant thumb for single- and dual-thumb gestures.

Gesture Size The size is also normally distributed (p_{S1}=.0.81, p_{S2}=.99). A paired t-test discovers a variation in size for S1 (t(35)=-6.080, p<.001) along with S2 (t(35)=-9.114, p<.001). The non-dominant thumb achieves an average size of 2.99 cm (SD=1.28 cm) in S1 and 1.59 cm (SD=0.65 cm) in S2. The sizes of the dominant thumb are larger with 3.38 cm (SD=1.21 cm) for S1 and 2.31 cm (SD=0.83 cm) in S2.

H3: Dominant thumb characteristics differ between single- and dual-thumb gestures
We compare the single-thumb gestures G1 and G3 with their in-phase and dual-thumb correspondences, i.e., gestures G4 and G5.

Gesture Speed The hypothesis that the data comes from a normal distribution cannot be rejected (p_{S1}=.32, p_{S2}=.34). A paired t-test reveals speed differences ($t_{S1}(35)$=4.807, p_{S1}<.001, $t_{S2}(35)$=4.541, p_{S2}<.001) in both scenarios. Figure 6 shows that the average single-thumb speed is 17.34 cm/s (SD=6.45 cm/s) and the dual-thumb speed is 14.75 cm/s (SD=6.68 cm/s) in S1. In S2, the single-thumb and dual-thumb speeds are 22.98 cm/s (SD=5.86 cm/s) and 19.66 cm/s (SD=5.32 cm/s), respectively.

Gesture Size S1 is not normally distributed (p_{S1}<.01) but S2 (p_{S2}=.57). The gesture sizes do not differ significantly in both scenarios (V_{S1}=391, p_{S1}=.37, $t_{S2}(35)$=1.147, p_{S2}=.26). The average sizes of single-thumb gestures are 3.36 cm (SD=1.24 cm) in S1 and 2.42 cm (SD=0.99 cm) in S2, whereas the corresponding dual-thumb gesture sizes are 3.38 cm (SD=1.21 cm) and 2.31 cm (SD=0.83 cm) in S1 and S2, respectively.

Subjective Feedback
Figure 7 illustrates the average R-TLX of each gesture. It is identifiable that users ranked effort, frustration and performance of dual-thumb gestures higher than of single-thumb gestures. The effort, frustration and performance were ranked lowest for G2. Thus, this gestures can be easiest accomplished by the users. The temporal rating was lowest for G3, even though no significant difference in gesture speed or size could be discovered for H1 in S2. Interestingly, the physical and mental strain of single- and dual-thumb gestures are similar.

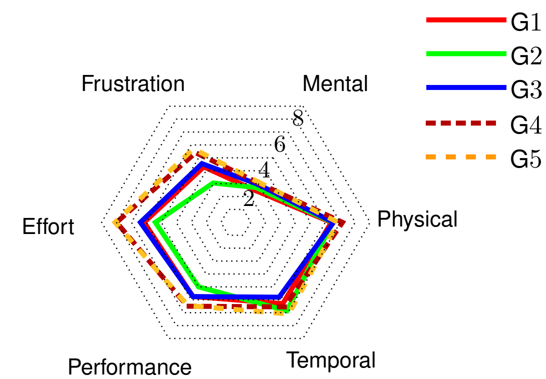

Figure 7: R-TLX of all gestures.

Discussion & Conclusion

The single-thumb speed depends both on the axis and the movement direction in S1. Consequently, the users completed gestures faster for vertical (23.53 %) and upward (15.63 %) motions, but only if no time-pressure was imposed on them. When requesting high performance (S2), the users accomplished similar gesture speeds regardless of axis and direction. That is why H1 is only true for S1 and not for S2. Moreover, the gesture size is only larger for vertical thumb motions (18.50 %) in S1. In S2, the users moved their thumb as fast as possible, which reduced the average gesture size in comparison to S1 (Δ=-0.95 cm) and no difference between axis and direction can be observed anymore. In conclusion, an upward thumb movement matches best with the thumb biomechanics leading to the highest values in the metrics. The easiest gesture (R-TLX), however, is a downward thumb movement. A high performance task (S2) voids these differences.

Dual-thumb Interaction
The dominant thumb is faster during dual-thumb gestures than the non-dominant thumb. Furthermore, the gesture sizes of the dominant thumb differ to the non-dominant thumb with a gain of 13 % and 45 % in S1 and S2, respectively. H2 is true, thus a dynamic thumb interaction model should incorporate faster and larger gestures for the dominant-thumb.

We also evaluated speed differences between single- and dual-thumb gestures. Here, the speed of single-thumb gestures is higher in both scenarios. However, the gesture sizes of the dominant thumb remain the same regardless of the number of thumbs. In conclusion, H3 is only true for the gesture speed. A dynamic thumb model should expect higher gesture speeds for single-thumb interactions. Additionally, dual-thumb interactions require more effort than single-thumb interactions, even though physical and mental strain are the same. For the ease of use, thumb-based touch interfaces should foster single-thumb inputs.

Based on these two hypotheses, we assume that in the dual-thumb case the dominant thumb adapts its speed to the non-dominant thumb. Thus, a synchronization of the thumbs occurs, leading to lower peak speeds of the dominant thumb. The non-dominant thumb is still slower as the dominant thumb, though.

Future Work

Based on our findings, mapping functions between the gestures and the desired interactions, e.g., 3D object manipulation [15], can be elaborated. For instance, the mapping functions can take the average and maximum speed of a single-thumb gesture into account. Future work can exploit our results about the thumb dynamics and handedness effects to create a dynamic thumb interaction model similar to the work of [2].

We discovered differences between S1 and S2. For instance, all gestures in S2 were of shorter size than in S1. Furthermore, the differences between the average speeds in S1 and S2 are larger for the dominant thumb (Δ=4.91 cm/s) than for the non-dominant thumb (Δ=0.77 cm/s). Future work should detail how the scenario influences the gesture characteristics. Besides our proposed scenarios, it would be interesting to know whether gesture characteristics change if they are just a secondary task, e.g., in a touch-based game.

REFERENCES

1. CA Armstrong and JA Oldham. 1999. A comparison of dominant and non-dominant hand strengths. *SAGE Journal of Hand Surgery* 24, 4 (1999), 421–425. DOI: http://dx.doi.org/10.1054/JHSB.1999.0236
2. Joanna Bergstrom-Lehtovirta and Antti Oulasvirta. 2014. Modeling the Functional Area of the Thumb on Mobile Touchscreen Surfaces. In *Proc. CHI*. ACM, 1991–2000. DOI: http://dx.doi.org/10.1145/2556288.2557354
3. Marie-Luce Bourguet and Akio Ando. 1998. Synchronization of Speech and Hand Gestures During Multimodal Human-computer Interaction. In *Proc. CHI*.

ACM, 241–242. DOI: http://dx.doi.org/10.1145/286498.286726

4. Chi Tai Dang, Martin Straub, and Elisabeth André. 2009. Hand Distinction for Multi-touch Tabletop Interaction. In *Proc. ITS*. ACM, 101–108. DOI: http://dx.doi.org/10.1145/1731903.1731925
5. George ElKoura and Karan Singh. 2003. Handrix: Animating the human hand. In *Proc. SCA*. ACM, 110–119.
6. Sandra G Hart and Lowell E Staveland. 1988. Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. *Elsevier Advances in Psychology* 52 (1988), 139–183. DOI: http://dx.doi.org/10.1016/S0166-4115(08)62386-9
7. WE Hook and JK Stanley. 1986. Assessment of thumb to index pulp to pulp pinch grip strengths. *SAGE Journal of Hand Surgery* 11, 1 (1986), 91–92. DOI: http://dx.doi.org/10.1016/0266-7681(86)90024-0
8. Mary C. Hume, Harris Gellman, Harry McKellop, and Robert H. Brumfield. 1990. Functional range of motion of the joints of the hand. *Elsevier The Journal of Hand Surgery* 15, 2 (1990), 240–243. DOI: http://dx.doi.org/10.1016/0363-5023(90)90102-W
9. Nurgul Arinci Incel, Esma Ceceli, Pinar Bakici Durukan, H Rana Erdem, and Z Rezan Yorgancioglu. 2002. Grip strength: Effect of hand dominance. *Singapore Medical Journal* 43, 5 (2002), 234–237.
10. Kenrick Kin, Maneesh Agrawala, and Tony DeRose. 2009. Determining the Benefits of Direct-touch, Bimanual, and Multifinger Input on a Multitouch Workstation. In *Proc. GI*. ACM, 119–124.
11. Tomer Moscovich and John F. Hughes. 2008. Indirect Mappings of Multi-touch Input Using One and Two Hands. In *Proc. CHI*. ACM, 1275–1284. DOI: http://dx.doi.org/10.1145/1357054.1357254
12. Anna Pereira, Tevis Miller, Yi-Min Huang, Dan Odell, and David Rempel. 2013. Holding a tablet computer with one hand: effect of tablet design features on biomechanics and subjective usability among users with small hands. *Taylor & Francis Ergonomics* 56, 9 (2013), 1363–1375. DOI: http://dx.doi.org/10.1080/00140139.2013.820844
13. Bruno H. Repp. 2005. Sensorimotor synchronization: A review of the tapping literature. *Springer Psychonomic Bulletin & Review* 12, 6 (2005), 969–992. DOI: http://dx.doi.org/10.3758/BF03206433
14. Tao Sun and Christopher A Walsh. 2006. Molecular approaches to brain asymmetry and handedness. *Nature Reviews Neuroscience* 7, 8 (2006), 655–662. DOI:http://dx.doi.org/10.1038/nrn1930
15. Philipp Tiefenbacher, Andreas Pflaum, and Gerhard Rigoll. 2014. Touch gestures for improved 3D object manipulation in mobile augmented reality. In *Proc. ISMAR*. IEEE, 315–316. DOI: http://dx.doi.org/10.1109/ISMAR.2014.6948467
16. Fredrik Ullén, Hans Forssberg, and H Henrik Ehrsson. 2003. Neural networks for the coordination of the hands in time. *APS Journal of Neurophysiology* 89, 2 (2003), 1126–1135. DOI: http://dx.doi.org/10.1152/jn.00775.2002
17. Julie Wagner, Stéphane Huot, and Wendy Mackay. 2012. BiTouch and BiPad: Designing bimanual interaction for hand-held tablets. In *Proc. CHI*. ACM, 2317–2326. DOI: http://dx.doi.org/10.1145/2207676.2208391