Fingers and Angles: Exploring the Comfort of Touch Input on Smartwatches

HYUNJAE GIL, Department of Human Factors Engineering, UNIST, Republic of Korea
HONGMIN KIM, Department of Human Factors Engineering, UNIST, Republic of Korea
IAN OAKLEY, Department of Human Factors Engineering, UNIST, Republic of Korea

Smartwatches present a unique touch input context: small, fixed to one wrist and approachable from a limited range of angles by the touching hand. Techniques to expand their input expressivity often involve variations in how a watch must be touched, such as with different fingers, poses or from specific angles. While objective performance with such systems is commonly reported, subjective qualities such as comfort remain overlooked. We argue that techniques that involve uncomfortable input will be of limited value and contribute the first data on the comfort of input on smartwatches via two studies that combine subjective ratings of comfort with objective performance data. We examine both static and dynamic touches and three finger poses. Based on the study results, we contribute a set of design recommendations for comfortable, effective smartwatch input. We close by instantiating the recommendations in interface prototypes that we evaluate in a final qualitative study.

CCS Concepts: • **Human-centered computing → Touch screens**; **Empirical studies in HCI**; **Pointing**;

Additional Key Words and Phrases: Smartwatch, Comfort, Touch Input, Angular Input

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1 INTRODUCTION

Wrist worn wearables such as smartwatches have a unique input context. Their mounting point on the forearm provides benefits: a ready visual availability [7] and an easily adjustable device position that makes them suitable for novel input styles such as arm gestures [41]. On the other hand, their small touch and display surfaces present substantial challenges for input techniques, such as multi-touch, that have been instrumental in the popularization of larger scale mobile devices such as smartphones. Researchers have begun to explore the opportunity this represents with proposals for how touch interaction can be customized for the constraints of the watch form factor. Ideas include the use of pairs of fingers in temporal [30] or spatial [20] patterns, or distinguishing amongst touches based on properties such as contact area shape [31] or the finger issuing the touch [11]. The goals of this work are typically to improve expressiveness and/or speed of input.

However, little attention has been paid to how physically comfortable these techniques are to use. We argue this issue is particularly relevant for interaction on smartwatches as they are operated with a specific and highly limited pose between the arm wearing the watch and the arm/finger touching the screen. Many of the techniques

Authors' addresses: Hyunjae Gil, Department of Human Factors Engineering, UNIST, Ulsan, Republic of Korea, hyunjaegil@gmail.com; Hongmin Kim, Department of Human Factors Engineering, UNIST, Ulsan, Republic of Korea, khm489@gmail.com; Ian Oakley, Department of Human Factors Engineering, UNIST, Ulsan, Republic of Korea, ian.r.oakley@gmail.com.

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authors have designed imply substantial variations in this pose that may, in turn, result in reduced comfort. This is most clear in the growing body of work that deals with yaw rotation of touches [43], or techniques based on the angle derived from the shape of a single finger touch [31] or that between a pair of finger touches [20]. In these examples, users perform tasks such as menu selection, parameter setting or shortcut activation by specifying angles in ranges of between 120° and 180°, spans that imply substantial movements of one or both hands or arms. They also achieve these manipulations using touches issued by a range of different finger areas such as the flat [43] or side [31] of the thumb, index or middle fingers and the combination of index and middle finger [11] and/or index and thumb [20]. While reports on the accuracy, speed and reliability of these systems are staples in this literature, we highlight the fact that there is no data or commentary about how comfortable they are to use. Specifically, in these representative examples, comfort is not mentioned and even reports of high level data such as NASA TLX [14] or BORG-10 [2] are absent. This paper argues that the comfort of interacting with a smartwatch will vary substantially depending on both the angles users need specify and the finger area or areas they use to do so and seeks to gather data to elucidate this issue.

Comfort is a key issue in the design of touchscreen input techniques [5]. Regardless of how rapidly or accurately an input action can be performed, one that results in discomfort will be neglected over more comfortable alternatives. While prior work on larger form-factor devices suggests this is particularly true of touches specifying angle information [25], no work to date has examined the comfort of input of smartwatches. Accordingly, this paper gathers and contributes baseline data on the comfort of input on smartwatches from a pair of studies that combine and contrast traditional metrics of time and accuracy with ratings of the comfort of touches. These experiments were designed to directly complement prior work reporting objective aspects of input performance – they focus on representative input tasks. Specifically, we consider eight different angles and three different finger regions: the flat of the index finger, the side of the index finger and the tips of index and middle fingers. The first study involves static touches – atomic touches and releases of the screen that indicate a single angle. This type of touch appears in prior smartwatch input techniques, such as Lafreniere et al. [20]'s description of pairs of variously angled simultaneous taps on a 3x3 grid of targets covering a smartwatch screen. The results highlight viable, comfortable ranges for angular input for each of the three finger regions. Building on these findings, a follow up study captures the comfort and performance of dynamic touches involving on screen rotations from one input angle to another, a form of input that has been proposed in, for example, Xiao et al. [43]'s description of yaw input. This paper complements this existing work with its focus on the comfort of input. The paper closes by contributing practical recommendations for input on smartwatches in terms of the angles and finger regions that users can comfortably and effectively use. We showcase the value of these recommendations by designing interaction techniques that instantiate them and capturing user reactions to the applications, and interaction techniques they feature, in a final qualitative study.

2 RELATED WORK

The small size and worn context of smartwatches presents new challenges and opportunities for the design of input and interaction techniques. Approaches are as diverse as adapting existing primitives such as tap [24], swipe [19] or multi-tap [30] to small screens, extending input spaces to the skin areas surrounding a device [21] or leveraging different aspects of the worn context of a watch. For example, a watch's loosely anchored attachment to the body enables it to be pushed or twisted, providing a rich space for input [42; 44], and its proximity to the hand can enable various forms of gestural input, what Kerber et al. [17] term "same-side" interactions, such as detecting finger motions [41] or simple tilts of the arm [38] or wrist [10]. Wearables are also inherently available for use in wide range of settings and researchers are being to characterize user performance while mobile or encumbered [6] and to present design guidance to better enable the use of watches in these distracted and complicated scenarios [35].

Comfort is an important aspect of wearable device use and a valuable lens though which new input techniques can be examined. A practical definition revolves around movements that can be readily achieved – for example in Le et al. [23], "comfortable areas" are defined as regions that can be reached by the fingers, during single handed use of a smartphone, without hand posture or grip changes. Based on this definition, comfort and input involving variations in the angle between the sensor surface and the touching finger are intrinsically linked. Hoggan et al. [15], in one of the relatively few studies to systematically examine human performance of multi-touch rotations, introduce a notion of "ergonomic failure" to denote uncomfortable situations in which a rotation cannot be performed due to the fingers jamming against one another. Hoggan et al. [15] use a tablet sized touch surface, input with the index finger and thumb, initial touch angles in fairly extreme ranges (0-120°) and fixed 90° rotations. They report ergonomic failure led to abandonment of 39.7% of trials. However, despite acknowledging the importance of comfort in this interaction, they provide no data on how comfortable participants felt any of the tasks they actually completed were – we argue that prior to failure, there is likely to be a spectrum of more and less comfortable actions.

Other authors have also sought to formalize performance of general multi-touch input, including rotational tasks. Nguyen and Kipp [28], for example, explore performance of combined rotation and translation operations on a multi-touch table using a Fitts law [36] study design. Using a similar tabletop setup, Zhao et al. [45] examine the full set of translation, rotation and scaling operations with the objective of creating a model of human performance for multi-touch input. Both articles also discuss the strategies and approaches users adopt to combine different types of transformation into single on-screen operations. However, we note that neither of these studies comments on the subjective qualities of the tasks their participants complete – their focus remains solely on production of objective models of performance. In closely related work, Voelker et al. [39] explore performance of rotational tasks in tangible and tabletop settings, concluding that grasping tangible, physical controllers can boost performance by 20%.

Numerous authors have also proposed rotation input using single fingers [40; 43], but the focus has typically been on system rather than user performance; there are few accounts of objective usage data, let alone subjective experience. One notable exception is Mayer et al.'s recent work on the ergonomics of single finger rotation input on tabletops [25] and mobile devices [27]. For both settings, this work considers touches with the finger tip from four pitch and 16 yaw finger angles (spanning a full 360) and captures subjective ratings of the feasibility of these angular touches. Among other analyses, these are used to define a comfort zone for touch input with each hand. On the tabletop, these are a 135° region where the touching finger can make contact with the screen while remaining aligned approximately parallel to the arm. In the mobile setting, these regions are larger: 180°. This is likely due to participants moving the touch surface (on a mobile device) during the course of their input. This work highlights the importance of comfort in performing input that involves different angles on a touch surface – it argues that input that is not comfortable is infeasible.

The work in the current paper extends these ideas in two key ways. First, it moves from a tabletop or mobile device scenario to that of a wrist wearable, a physically distinct input setting. Prior work on the biomechanical aspects of touch input, although not directly considering a wearable scenario, has highlighted the fact that touch input performance fundamentally differs depending on device form-factor and body posture [1] – different devices and postures engage different muscle groups, enable different movement ranges and result in different performance. The unique constraints of touch input on wearables, with small touch surfaces attached to the body, mean that findings from other input scenarios are unlikely to be directly applicable: new studies of performance in wearable settings, such as the one described in this work, are required. Secondly, this paper considers three different touch input techniques for specifying input angles: touches by the side and flat of the index finger and those by the pair of index and middle fingers. In this way, this paper complements prior work by improving our understanding of the comfort of touch input on a new form factor of wearable devices and with a larger set of finger regions.

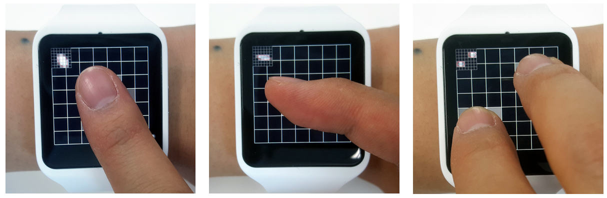

Fig. 1. Sony Smartwatch 3 capturing raw touch input; data shown in callout at top-left of screen. The three images show the finger regions used in this work. Left image shows a touch with the *flat* finger region, center with the *side* and right with *pair*.

3 SENSING ROTATIONS

All work in this paper was implemented on a Sony Smartwatch 3, a device with a 28.25mm square screen and a bevel of between 5 and 7mm. Following prior authors [16; 22; 43], and in order to capture rotations reliably, we adapted open source modifications to the Android kernel [9] to report raw touch data from the device's seven by seven sensor capacitive grid. Our implementation ran at 80Hz, sufficient to provide a fluid response. We calculated ellipses through a process of flood filling to isolate individual touch areas and image moments to derive their description: centroid, orientation, the size of major and minor axes and eccentricity. We thresholded sensor data at 25% of its maximum value and, unlike prior work [43], did not apply any gamma corrections to the touch image. Both the system's similarity to those deployed in prior studies [43] and extensive iterative testing during development indicate this configuration recorded input angles relatively accurately – this approach leads to errors of approximately 10°, as reported by Xiao et al. [43] in their description of yaw detection accuracy for flat (low pitch) touches. We argue this level of accuracy is both realistic (e.g. supported by standard touchscreen sensor arrangements) and sufficient to support our empirical objectives – to elicit particular angular inputs in order to assess their comfort.

We acknowledge that more advanced algorithms have been proposed to extract finger angle from touch screen input patterns, such as the deep learning approach proposed by Mayer et al. [26], but we argue that while these techniques can boost angular accuracy, their relatively high computational overhead makes them unsuitable for interactive tasks on resource constrained devices such as smartwatches. Furthermore, the benefits of these advanced algorithms are not clear for the scenario in this paper – while Xiao et al. [43] report genuine data from a watch, Mayer et al. [26] use a larger touch surface and note that their results may not generalize to small screens where finger contact regions may be truncated at sensor edges. Furthermore, while Mayer et al. [26]'s detailed critique highlights improvements in accuracy over Xiao et al. [43] yaw accuracy, it is not clear these apply to the situation in which fingers are flat on the touch-screen surface (low-pitch). Performance of Xiao et al. [43]'s heuristic algorithm is optimal in this setting and variations in reporting in Mayer et al. [26] make it hard to assess whether their algorithm offers improvements when fingers are flat. This combination of suitability for use in an interactive study (rather than the purely measurement scenario in Mayer et al. [26]) and proven performance in a wearable setting motivated our choice of Xiao et al. [43]'s implementation for the current work. Figure 1 shows the watch with a callout visualizing the sensor data.

4 STATIC ANGLE STUDY

We first captured performance and comfort data during production of static angles using three common finger regions: the *flat* or *side* of the index finger and the *pair* of index and middle fingers – these are shown in 1. The flat and side of the index finger were selected as they are the only two ways on-screen yaw angles can be specified by a single digit. They have also been explored in prior work [9; 25; 43]. We opted to study index plus middle over the alternative pair of index plus thumb as it has also been specifically studied in prior work [11]. We also

Fig. 2. Left image shows eight angular targets and smartwatch used in the static study. Targets are subsequently referred to by the degree angles 30° through 240°. Right image shows the smartwatch with the study interface worn by a user about to select the 120° target with the side of their finger.

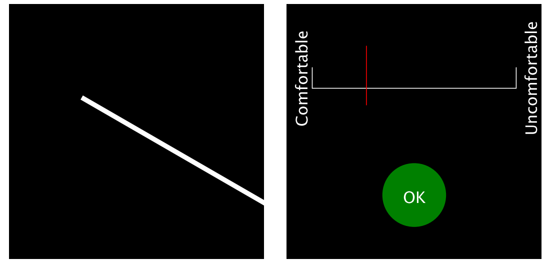

Fig. 3. Screen shots of watch interface from static study. Left image shows angle instruction for touching the target at 120° in the form of a simple white line. Right image shows the comfort scale used to enter ratings. To enter a rating, participants positioned the red line on the slider and then clicked OK.

selected a range of input angles to consider based on those proposed by prior work [25] and common sense plausibility – we excluded angles that would require a user initiate touches from the far side of arm wearing the watch as these would involve the touching hand reaching over the wrist wearing the watch and twisting back to touch the screen. This would be an inherently uncomfortable arrangement and indeed, prior work suggests that users may find this kind of task impossible to perform [25]. To select angles, we assumed the watch was always mounted on the left wrist and defined a range of 210°, spanning the clock position numerals between one and eight and aligned to the axes of the watch. Within this range, we considered eight angles, spaced at 30° clock position intervals. Following [43] we label these angles in degrees and sequentially in the clockwise direction with a zero point at the top: between 30° and 240°. Figure 2 shows these angular targets on the Sony smartwatch used in the studies.

The study followed a fully balanced repeated measures design for the three finger region conditions. Before each condition started, the experimenter explained the finger region to be used, demonstrating this if required, and emphasized the focus on comfort and that, within the constraints of the task, participants were free to touch the watch any way they liked. This included moving both arms, as well as the wrist and finger joints of hand touching the screen. One consequence of this approach is that, for pair touches, participants could use the index finger to mark either the edge or center of a specified angle: input for the opposing angles of 60° and 240°, for example, could be specified with an effectively identical pair of touches. Although an experimenter was present in the room throughout, the study did not include any external checks on participants' touches – the task was simple and consistent and we relied on participants to follow the finger region instructions faithfully.

Within each condition, participants completed two blocks of eight randomly ordered trial-sets, one for each angle considered in the study. Each trial-set was composed of five repetitions of the same angle followed by entering a rating about the experience on a single item continuous, unsegmented 100-point scale from comfortable (0) to uncomfortable (100), similar in structure to that used in Mayer et al. [25]'s closely related prior study. Participants in the current study were asked to rate "how comfortable the input was to perform". This question, and the scale labels, differs from that used by [25] (a question about feasibility and an explicit option to indicate an input was not feasible) as our core concern relates to comfort, and as such, our study design already excluded extreme angles that participants would likely perceive as impossible. The inclusion of five repetitions before each rating was intended to increase the reliability of the data (as it would be derived from a sustained experience), while the temporally separated repetition of ratings for identical angles in the two blocks provided a way to verify each participants' consistency.

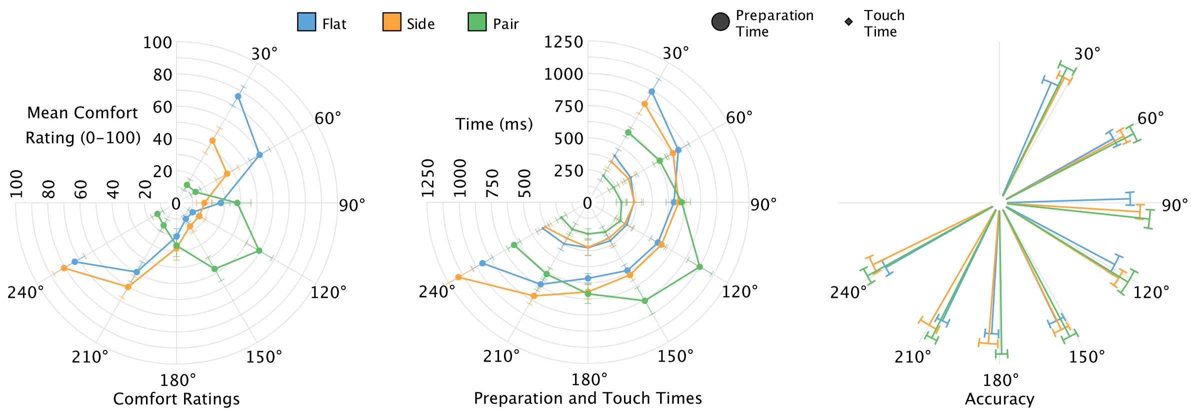

Fig. 4. Data from the static study: Comfort Ratings (left) on scale from Comfortable (0) to Uncomfortable (100); Preparation and Task Time (center) and; Angular Accuracy (right). Bars show standard deviation.

Eighteen participants completed the study (three in each possible order). They were recruited online from the local student population, screened for right-handedness and compensated with 10 USD in local currency. Nine were male and nine were female and they had a mean age of 21.6 (SD 1.8). They reported high levels of experience with touch screen smartphones (4.8/5) but low levels of experience with smartwatches and other wearables (1.25/5). In total the study resulted in 864 ratings derived from 4320 individual user inputs (18 participants by 3 finger regions by 2 blocks by 8 angles by 5 repetitions).

The structure of each trial was designed to solicit natural movements and poses – this stands in contrast to prior work on angle input which has tended to capture screen touches from controlled and somewhat artificial finger poses achieved by, for example, requiring participants to place their fingers in plastic guides [25; 43]. We argue these restricted settings are inappropriate for work focused on the comfort of wearable input; we need assess behavior in less artificial and constrained situations. Accordingly, we borrow from Lafreniere et al. [20] and had participants stand throughout the study. Furthermore, each trial in the study first instructed the participant to lower the arm wearing the watch to a vertical position with the hand over the thigh (detected via the device's accelerometer). After completing this, the arm was raised and a message requested them to tap the screen. A fixation spot was then displayed for 500ms, followed by a simple white line indicating the required angle. For each trial, we logged *preparation time* (from the presentation of an instruction until the first screen touch), *touch time* (the duration of a screen touch) and the absolute *accuracy* of the angle data at the temporal center of the touch [27]. The accuracy was calculated as the absolute difference between the target angle and either the orientation of one touch, or the angle specified by a pair of touches. We did not judge the success or failure of trials based on the accuracy. Finally, we also recorded all raw sensor data. After a trial-set was complete, participants entered a *comfort rating* using a slider shown on the watch. Study instructions are pictured in Figure 3.

4.1 Results

Figure 4 shows comfort (left), time (center) and accuracy (right) data per finger region and input angle. We first assessed the consistency of participants' ratings by correlating data from the two blocks in each condition. This led to a mean correlation of 0.78 (SD 0.11), indicating a strong relationship. This suggests that we can be confident in the validity of the data and that participants' subjectively experienced comfort was consistent throughout the study. Beyond this check, we analyzed each measure with a three by eight repeated measures ANOVA and *post-hoc* t-tests. We incorporated Greenhouse-Geisser corrections for sphericity violations and Bonferroni corrections to prevent alpha inflation in *post-hoc* testing. Based on longstanding arguments that this is appropriate, we opted to treat the data from the comfort rating scale as parametric [29]. At this stage in the analysis, we chose not to conduct *post-hoc* tests on the angle variable, as these would be aggregated over the three finger regions. Table 1 shows the statistical results.

4.2 Discussion

While the study showed significant differences in all variables, the comfort ratings led to the strongest effect sizes. This suggests this measure captures an important quality of behavior that should not be overlooked in the design of touch interfaces for wearables. The interaction effect between region and angle, clearly illustrated in Figure 4 (left), is strongest. It indicates that the comfort of specific angles varied with the finger regions used. We interpret this to mean that each pose has a different viable input range. To explore what these ranges might be, we calculated the overall mean comfort rating recorded in the study (37%) and performed three sets of Bonferroni adjusted pair-wise comparisons for the angle data from each finger region. This generated a large number of significant differences, but we note the key data is the Cohen's d effect sizes shown Table 2. These range from small to extremely large (large is typically defined as 0.8), reflecting the relative consistency of scores for each angle/finger region pair and the substantial differences between angles.

Table 1. ANOVA and post-hoc test results in static study.

Measure	*Variable(s)*	*Outcomes*			
Comfort	Region by Angle	$F(4.2,70.7) = 56.8$	$p < 0.001$	$\eta_p^2 = 0.77$	–
	Region	$F(2,34) = 16.71$	$p < 0.001$	$\eta_p^2 = 0.5$	*Post-hoc*: pair<side and flat (p<=0.002)
	Angle	$F(3.4,57.8) = 48.3$	$p < 0.001$	$\eta_p^2 = 0.74$	N/A
Preparation Time	Region by Angle	$F(3.3,55.6) = 26$	$p < 0.001$	$\eta_p^2 = 0.6$	–
	Region	$F(2,34) = 1.94$	$p = 0.16$	$\eta_p^2 = 0.1$	–
	Angle	$F(3.9,66.6) = 28.8$,	$p < 0.001$	$\eta_p^2 = 0.63$	N/A
Touch Time	Region by Angle	$F(5.2,70.7) = 88.18$	$p < 0.001$	$\eta_p^2 = 0.22$	–
	Region	$F(2,34) = 16.32$	$p < 0.001$	$\eta_p^2 = 0.49$	*Post-hoc*: pair<side and flat (p<=0.003)
	Angle	$F(3.4,57.8) = 48.3$	$p < 0.001$	$\eta_p^2 = 0.19$	N/A
Accuracy	Region by Angle	$F (14, 238) = 5.41$	$p < 0.001$	$\eta_p^2 = 0.24$	–
	Region	$F(2,34) = 0.87$	$p = 0.43$	$\eta_p^2 = 0.05$	–
	Angle	$F(4,68.3) = 1.92$	$p = 0.072$	$\eta_p^2 = 0.1$	N/A

Table 2. Cohen's d effect sizes for post-hoc pairwise comparisons on the comfort ratings for angles from 30° to 240° in the static study. One asterisk signifies a significant difference at p<0.05, two asterisks at p<0.01. All comparisons incorporate Bonferroni corrections.

Angle	*60°*			*90°*			*120°*			*150°*			*180°*			*210°*			*240°*		
	Flat	*Side*	*Pair*	*Flat*	*Side*	*Pair*	*Flat*	*Side*	*Pair*	*Flat*	*Side*	*Pair*	*Flat*	*Side*	*Pair*	*Flat*	*Side*	*Pair*	*Flat*	*Side*	*Pair*
30°	0.85**	0.35	0.07	2.75**	1.38**	1.4**	4.56**	1.5**	2.49**	4.84**	1.49**	1.99**	3.37**	0.71	0.9	1.36**	0.66	0.28	0.17	1.57**	0.08
60°				1.77**	1.03*	1.41*	3.29**	1.14*	2.53**	3.49**	1.13**	2.01**	2.3**	0.38	0.88	0.5	1.09**	0.22	0.67**	2.06**	0.01
90°							1.26*	0.07	0.85	1.36**	0.05	0.4	0.45	0.6	0.51	1.22*	2.42**	1.19**	2.52**	3.66**	1.35*
120°										0.01	0.03	0.48	0.82	0.69	1.44**	2.6**	2.62**	2.26**	4.22**	3.93**	2.43**
150°													0.89*	0.68	0.97**	2.76**	2.61**	1.76**	4.48**	3.93**	1.93**
180°																1.71**	1.51**	0.67	3.1**	2.51**	0.84
210°																			1.17**	0.98**	0.2

While these data could be interpreted in many ways, we make recommendations by thresholding data to be under the study mean and considering the effect size compared to the angle(s) with the best (lowest) comfort rating for each finger region (see Figure 4, left). Applying a threshold of 1.5 for effect size differences leads to selecting comfortable side touches as those between 60° and 180°, flat touches between 90° and 180° and pair touches from 0° to 90° or 180° to 270°. This dual viable range for pair touches is due to the fact that they involve approaching the watch from above, rather than from one side (as with the other two regions). As such, there is no practical difference between the opposing angles – a touch at 30° is effectively the same as one at 210°. This fact likely contributed to the significantly lower ratings that pair touches achieved in the main effect of region. We note that while data from the flat finger-region is broadly aligned with prior work on the comfort of input on tabletops [25], data for the other finger regions differs considerably, highlighting the value of exploring these alternative types of input. We speculate that the increased range in side over flat (the region from 60° to 90°) is due to participants' ability to use finger flexion during side input – bending the finger enables comfortable input over a larger set of angles. Similarly, we suggest the prominent increase in the discomfort of pair input around 120° is due to participants' need to to twist their wrist in order to align their index and middle fingers to make touches at this angle.

There are several other notable outcomes. Firstly, the significant interaction effects in the time and accuracy variables serves to reinforce the primary conclusion that specific angles were more or less challenging depending on the finger regions used. We also point out that the three significant main effects of angle likely reflect the fact that two conditions (flat and side) yielded relatively similar results, while pair data is almost opposite – this unbalanced split suggests these main effects can be discounted. Beyond this, touch times were significantly lower with the pair touches than with either flat (by 121ms) or side (by 99ms) touches, replicating prior descriptions of this kind of touch [25]. This effect may be due to participants' greater familiarity with two finger taps, or something intrinsic about these larger touches. Although they show few differences, the accuracy data are also useful for deriving viable angle target sizes: overall absolute mean and standard deviation were 3.7° and 2.47°. This suggests that angular targets should be approximately 20° wide to support easy acquisition – the mean plus two to three times the standard deviation in each angular direction. We note that the similarity of the accuracy measures provides a limited validation that the simple algorithm we use to assess angle in this work [43] is sufficient for our objectives. Specifically, assuming the human ability to specify angles in flat and side poses does not differ, the close similarity of the accuracy data for these two types of touch suggests that the algorithm is as accurate for side touches as for the flat touches on which it has previously been validated.

It is also worth discussing relationships among the different measures in the study – in particular, we are interested in assessing whether or not the comfort ratings genuinely capture unique aspects of user behavior or experience, or whether they simply replicate outcomes from more traditional objective data. To explore this issue, we correlated the full set of individual comfort ratings against both timing measures and the absolute accuracy data. As can been inferred from Figure 4, the results show some links: preparation time was moderately [8] correlated with comfort ($r=0.546$, $p<0.001$), but relationships with touch time ($r=0.066$, $p=0.17$) and absolute error ($r=0.025$, $p=0.603$) were non-significant. These outcomes clearly indicate that comfort is independent from accuracy (corresponding to error rate in more conventional studies) and time on screen during our static touch task. The similarity to preparation time is likely due to more awkward and uncomfortable poses requiring longer to produce. The fact the relationship is only moderate in strength, together with the higher effect sizes for comfort (and a visual inspection of Figure 4) suggest participants were able to maintain relatively high objective performance levels under conditions of moderate to substantial discomfort – mean preparation times exceed 1000ms in only a single pose/angle combination. A second implication from this data it is non-trivial to infer comfort from objective measures. In the current study, the only measure showing links is one that captures performance before screen contact – data that is easy to capture in a controlled lab study, but hard to observe in more naturalistic settings. These findings are important as, we argue, users are unlikely to adopt real systems that are uncomfortable to use, even if objective performance remains high. In this way, we argue that the results from this study highlight and support the value of explicitly measuring comfort.

Finally, we also examined the raw data from this study. Histograms on the eccentricity and major and minor axis lengths of the moments suggested that flat and side touches were highly distinctive – basically flat touches were considerably wider than side touches. In order to explore the feasibility of distinguishing between these two cases, we extracted a single centrally timed moment from each touch in the flat and side conditions and constructed a logistic regression model on this data using a ten-fold cross validation process in Weka [12]. This yielded an accuracy of 95.9%, a figure we suggest is high enough to make these distinguishing between side and flat touches a practical option.

5 DYNAMIC ANGLE STUDY

In order to further explore the differences between finger regions, we conducted a follow-up study of dynamic touches that involve rotations from an initial to a final angle. This type of input is a prominent feature of multi-touch systems [13] and has been proposed as a modality for single finger input on tabletops [40], mobile phones [32] and smartwatches [43]. While performance studies of multi-touch rotation exist [15], the majority of literature relating to single finger input is concerned with the accuracy with which angle can be determined by the sensing system [32; 43], or with interface design proposals. We are aware of no prior work that examines performance with the side of the finger, or which explicitly examines the comfort of the movements. This study sought to fill these gaps.

Eighteen new participants completed this study (11 male, 7 female, mean age 22.3 (SD 2.4)) recruited and screened as in the static study and with similar experience of smartphones (4.9/5) and wearables (1.6/5). For each of the three regions, we selected a 120° angular range centered on the most comfortable region identified in the static touch study. These were 60° to 180° (side), 90° to 210° (flat) and 150° to 270° (pair). We again spaced targets at 30° and each participant completed each region condition in a fully balanced design. The study design sought to explore key properties of targeting movements: distance and size (or width). While there are many paradigms studying these variables, we opted to build on prior work on rotation input [28] and use a Fitts law inspired study design. This is a well-validated experimental paradigm that confers numerous benefits including a formalism for selecting appropriate target properties (size/width) to study, guidance for designing, balancing and repeating trials, and detailed analysis procedures. Applying these perspectives to targeting study designs can increase the reliability and validity of the final outcomes. Based on this approach, trials for each finger region involved an exhaustive combination of all five start points to all four end points, leading to four movement distances in two directions (clockwise and anti-clockwise). We defined the angular width of the start target as 20° and included two possible angular widths for the end target: 5° and 15°. The two end target sizes and four distances led to eight Index of Difficulty (ID) values, spanning 1.58 to 4.64 and typical of those used in prior studies of rotation input [28]. The start width was set derived from data in the first study: the mean absolute accuracy plus 2.5 times the standard deviation in each angular direction. This target size was intended to provide a moderately challenging input task.

However, the study procedures deviated from Fitts law recommendations [36] in several major ways. Firstly, we focused on input in a natural setting - we maintained the study setup with standing participants who lower and raise the watch prior to each trial. This broke up the trials and increased the study duration. In total, for each region condition, we ran three blocks of randomly ordered trials involving all combinations of start-angle, end-angle and width. The first block was discarded as practice and, although the study took approximately one hour to complete, this led to too few trials to adjust for accuracy and calculate IDe [36]. Secondly, the largest angular distances (120°) could only be performed between one start and end point, whereas the smallest distances (30°) could be performed between any pair, leading to unequal numbers of trials for each ID value. To deal

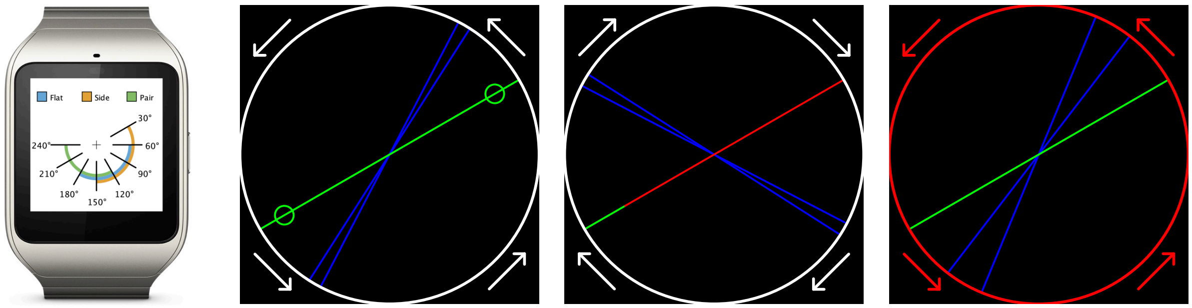

Fig. 5. Left image shows the 120° angle ranges used in the three finger-region conditions in the dynamic study. Right three images show screen shots of the watch interface from dynamic study. The large circle and arrows in the corners indicate the rotational direction for the trial. The circle and arrows are white at the start of a trial (center two images) and turn red when the screen is touched (right image). In each trial two targets are shown – the initial target users must touch at the start of a trial, marked by a single red/green line, and the final target, marked by a symmetric blue wedge. After touching the initial target. the single red/green line serves as a cursor and the user's task is to rotate it so that it is within the blue wedge. Highlighting on the initial target indicates how it should be touched. Left-center shows two small circles, used to show appropriate finger positions for the pair condition while the large red portion of the line in the right-center image shows the touch angle for flat/side conditions.

with these deviations, we explicitly logged trial correctness and had participants repeat erroneous trials, thus supporting separate analyses of time and error data.

The primary independent variable in the study was finger region. We also considered rotation direction (clockwise/counter-clockwise) and, in non-Fitts analyses, final target size. For each trial, we measured *preparation time* and *touch time*, as in the first study, as well as errors on both the initial touch and final release, respectively termed *initial errors* and *final errors*. Errors were defined as touch angles outside the specified start or end target regions. Based on these data, we calculated *throughput* [36] and also logged all raw sensor data. Finally, in order to assess comfort, participants filled a short paper questionnaire at the end of each region condition; the lack of sustained trial repetitions precluded capture of repeated comfort ratings as in the static study. However, participants answered the same question used in the static angle study: they rated both clockwise and counter-clockwise rotations using a comfortable-uncomfortable scale. This was also labeled identically (comfortable to uncomfortable) to the scale in the static study and, again similarly, no units were marked. However, in order to facilitate subsequent scoring by an experimenter, it was divided into 20 equal segments. We opted for a paper questionnaire due to the limited amount of data collected and to provide a non-watch based activity to break up study conditions. In total, we retained 4320 correct trials (18 participants x 3 finger regions x 2 blocks x 5 start-angles x 4 end angles x 2 widths) and 108 comfort ratings (18 participants x 3 finger regions x 2 directions) for analysis.

Instructions for the study were designed to maximize visibility on the small watch screen in all three finger region conditions. A circle was drawn full screen and the direction of the required rotation indicated by four arrows in the corners. The initial angle was always marked with a line across the circle, while the final angle and width were shown by symmetric wedges. During movement, the line acted as a cursor, following a user's rotation. The task was to move the line into the wedges. In the flat and side conditions, a colored highlight indicated that users should leave the tip of the line uncovered in order to receive feedback as to the current angle. In the pair condition, two small circles indicated where to touch to ensure the center potion of the line provided a similar response. We note these differences are an inevitable result of using different finger regions on a tiny screen. Figure 5 shows these interfaces.

5.1 Results

Data were analyzed using procedures similar to the static study: repeated measures ANOVA and post-hoc tests incorporating any necessary adjustments for sphericity violations and applying Bonferroni confidence intervals adjustments in *post-hoc* testing. Table 3 summarizes these outcomes for all variables. Data from the comfort ratings (not charted) showed no significant differences and an overall mean (11.08, SD 4.9) in the mid-range of the 0-20 scale used. Data per finger region were: flat (M: 10.11, SD: 4.91); side (M: 11.02, SD: 4.49) and; pair (M: 12.11, SD: 5.2). This suggests that the selection of angular zones to match finger regions was successful: participants experienced similar levels of comfort in each condition. Furthermore, the direction of movement (CW: 11.46, CCW: 10.7) did not impact comfort. However, the overall rating (55%) was higher than in the first study, suggesting that the dynamic task was found to be, on the whole, moderately less comfortable that the static task in the first study. As such, input techniques that rely on static touches may be preferred over those that require dynamic motion.

Analysis of input time showed more diversity. Time data are shown in Figure 6. All main effects were significant for preparation time, indicating that counter-clockwise motions towards large targets with side and pair finger regions led to optimal performance. We note the magnitude of some of these temporal differences (e.g. in the size variable) are quite small and may have limited real world impact. In contrast to the static study, touch time data revealed that side touches were significantly faster than pair or flat touches. Target size also strongly influenced performance. The main effect of region was borne out by generating Fitts' law regression models and calculating throughput for each region and direction. Direction did not yield significant variations, but side (mean of 1.79 bits/second, SD 0.06) significantly improved over flat (1.61, 0.07) and pair (1.62, 0.08). We note that, as we did not include accuracy adjustments in these models (i.e., we used ID not IDe), they simply represent temporal peak performance, rather than more nuanced figures that incorporate an error term. In contrast to the data from the

Table 3. ANOVA and post-hoc test results in dynamic study. Data from non-significant interaction effects are not presented.

Measure	*Variable(s)*	*Outcomes*			
Preparation Time	Region by Direction	F(2,34) = 5.9	$p < 0.006$	$\eta_p^2 = 0.26$	–
	Region	F(1.4,23.7) = 9.24	$p < 0.003$	$\eta_p^2 = 0.32$	*Post-hoc*: flat>side and pair (p<=0.009)
	Direction	F(1,17) = 27.45	$p < 0.001$	$\eta_p^2 = 0.62$	–
	Size	F(1,17) = 10.06	$p < 0.001$	$\eta_p^2 = 0.37$	–
Touch Time	Region	F(2,34) = 5.96	$p < 0.006$	$\eta_p^2 = 0.26$	*Post-hoc*: side<flat and pair (p<=0.046)
	Direction	F(1,17) = 0.65	$p = 0.43$	$\eta_p^2 = 0.04$	–
	Size	F(1, 17) = 440.7	$p < 0.001$	$\eta_p^2 = 0.96$	–
Throughput	Region	F (2,34) = 8.22	$p < 0.001$	$\eta_p^2 = 0.33$	*Post-hoc*: side>flat and pair (p<=0.026)
	Direction	F(1,17) = 0.37	$p = 0.85$	$\eta_p^2 = 0.002$	–
Initial Errors	Region by Direction	F(2,34) = 16.3	$p < 0.001$	$\eta_p^2 = 0.49$	–
	Region	F(2,34) = 30.7	$p < 0.001$	$\eta_p^2 = 0.64$	*Post-hoc*: pair<side and flat (p<=0.001)
	Direction	F(1,17) = 6.2	$p < 0.023$	$\eta_p^2 = 0.27$	–
	Size	F(1,17) = 3.51	$p = 0.078$	$\eta_p^2 = 0.17$	–
Final Errors	Region by Size	F(2,34) = 3.81	$p < 0.032$	$\eta_p^2 = 0.18$	–
	Region	F(1,17) = 0.72	$p < 0.5$	$\eta_p^2 = 0.04$	–
	Direction	F(1,17) = 0.94	$p < 0.35$	$\eta_p^2 = 0.05$	–
	Size	F(1,17) = 82.58	$p < 0.001$	$\eta_p^2 = 0.83$	–

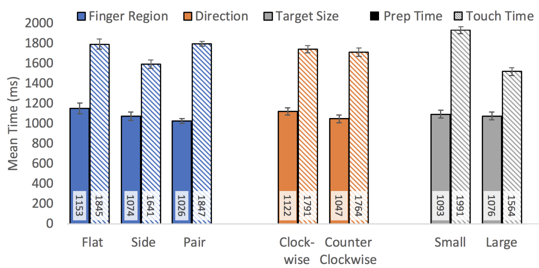

Fig. 6. Preparation and Touch time data from dynamic study organized by three main effects. Bars show standard error.

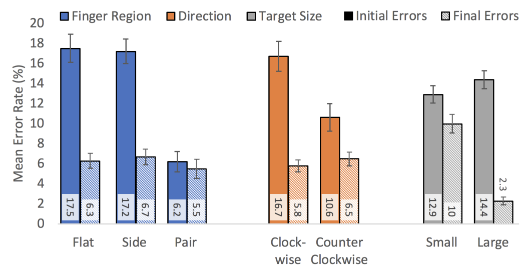

Fig. 7. Errors in initial and final touches in dynamic study organized by three main effects. Bars show standard error.

static study we conclude that, for the 120° angular input areas we studied, touches using the side finger region provide an optimal combination of fast preparation and touch times for dynamic tasks. A likely reason for this is that participants could use finger flexion [18] in addition to hand and wrist movements during input.

Error rates are shown in Figure 7. The dominant result from the initial touch error data was that this was lowest in the pair condition, although still somewhat high (6.2%). While this indicates that pair touches are more accurate, it also suggests that larger initial targets are needed in general. It is also higher than predicted based on the accuracy data in the first study – success rates of 97% could be expected with targets set to 2.5 times SD of recorded touch accuracy. This may indicate that preparing to complete the dynamic task influenced the accuracy of participants' initial touches – they may have commenced rotational movements prior to screen touches due to a focus on the final steps of the task rather than the initial ones. Counter-clockwise rotations also led to significantly lower initial errors than clockwise rotations, indicating that the initial stages of this movement can be achieved more accurately.

Final error data flesh out these findings. We note that before analyzing these data, we removed trials involving very short touches (more than 3.5 standard deviations from the mean) as these were likely due to unintentional artifacts of the experimental procedure rather than genuine attempts to complete the trials. It total, this accounted for 1.43% of total trials, evenly distributed over the different finger region conditions. The strong main effect of size dominated the final error results, revealing a very substantial difference between the high error rates with small 5° targets and very low rates with the 15° targets. In fact, even though the large final targets were smaller than the initial targets, they recorded much lower error rates, most likely due to the fact that performance was guided by a cursor.

Finally, in order to validate the logistic regression model that distinguished between flat and side touches in the static study, we tested it with data from the dynamic study. We once again extracted a single moment from the center of each flat and side trial, and used this data as a test set for the previously generated Weka model. This led to an accuracy of 95.6%, very similar to that recorded in the static study. This strongly suggests that touches with flat and side finger regions can be reliably distinguished from each other across all users and a range of different tasks.

5.2 Discussion

The goal of this study was to apply the outcomes from the static angle study, in terms of the comfortable input ranges, in a more complex setting. The primary result from this study is that the flat comfort ratings suggest these recommendations are valid - participants did not rate any of the input conditions in the study as more or less comfortable than any other. This is a positive result that suggests that future researchers and designers will be able to apply the comfortable angular input ranges and finger region combinations we propose to help them create novel smartwatch input techniques. We also note that these ranges not only differ between the different finger regions, but also from those identified in prior work [25; 27] on other platforms. This highlights the importance of assessing comfort for different device form factors.

A second key finding relates to temporal aspects of performance. In contrast to the static study, participants performed most rapidly with input via the the side of the finger – they showed a 10% – 11% increase in throughput during correctly performed trials, most likely due to the use of finger flexion during input. This result suggests that interaction techniques that rely on input via the side of the finger (e.g., [9]) may be particularly suitable for the watch form factor. In contrast to other devices, the small size and wrist mounted location of a smartwatch may make it uniquely accessible to touches with the side of the a finger. Its also worth contrasting rotational input performance in this study with prior work. While differences in methods and setting make direct comparisons impossible, the 2.4s–3.2s mean task completion times in the current study are broadly similar to those reported in prior work, such as the 2.5s–3s reported for two finger rotations of between 60° and 120° degrees on tablets by Hoggan et al. [15] and Voelker et al. [39]'s report of approximately 1.8s movement times for two finger rotations of between 50° and 150°. This latter result broadly matches the mean 1.44s touch time in the pair condition for targets that are between 30° and 120° degrees distant. These comparisons suggest that, despite their small size, rotation input is achievable on smartwatches at similar speeds to those attained on much larger input surfaces.

Beyond these points, we discuss the remainder of the study results in combination with those from the static angle study and in the form of recommendations for design. These are presented in the following section.

6 DESIGN RECOMMENDATIONS

The studies support a range of recommendations for the design of smartwatch interfaces based on both the objective and subjective data. We collect these by theme below:

Input ranges: The comfort ratings from the first study show viable angles for input on smartwatches using three different finger regions. Based on differences from the most comfortable angles, and a threshold approximating the mean overall comfort rating, the side region is viable between with angles from 60° to 180°, the flat between 90° and 180° and two finger touches of the index and middle fingers between 180° and 270° (and/or 0° and 90°). We suggest that interface designs that require poses outside of these ranges are not likely to be well received by users. The objective data back this up: in the first study, preparation times increase in a moderately similar pattern to comfort, suggesting it is takes more time to adopt a pose suitable for input outside of these comfortable ranges. Data from the dynamic study, where comfort (and to some extent preparation time) are less variable, support these conclusions – designing for comfortable ranges of motion will increase usability of input techniques. We note that these comfortable input ranges extend those proposed in prior work on tabletops [25] and mobile devices [27] by considering a range of finger regions and focusing on smartwatch input – a context where both the device and touching finger are able to move.

Target sizes: The studies provide a rich characterization of pitch angle target sizes for smartwatch input based on standard touchscreen sensing technology. We consider three scenarios: a feedback-free absolute task in the static study, a variant of this task including only correctness feedback for initial touches in the dynamic study and a cursor driven task for final touches in the dynamic study. We can make a number of recommendations. For initial touches, a minimum target angular width would be 20°, as recommended in the static study. If tasks involve subsequent on-screen movements, larger targets of 30° or more are recommended. For tasks involving selection on release and a cursor indicating current angle, sizes can be lower: the 15° targets in the dynamic study led to near error-free performance. While these figures represent safe minimums, it is worth noting that more accurate finger angle detection technologies (e.g. with less than the approximately 10° of error expected with our system [43]) may enable effective use of smaller targets.

Static vs Dynamic: We noted a range of performance variations between the static and dynamic studies. While we did not perform a direct comparison, mean percentage comfort ratings are better for static touches, even though we considered a broader range of angles. This suggests that participants found the dynamic movements more generally uncomfortable than the static touches: these simpler inputs should be used when possible. Objective performance also differed between these two scenarios. Specifically, we note a switch in touch time data. Optimal static touches were performed with the index and middle fingers, while optimal dynamic touches were performed with the side of the index finger. This suggests that different finger regions may be more and less suitable for these different types of input.

Distinctive touches: While distinguishing between paired and single touches is a trivial and commonplace part of modern interfaces, the data reported in this paper indicates we can also distinguish between flat and side finger regions. Using a simple regression model, we attained a high degree of accuracy (~95%) that was valid across different participants and tasks. While authors have previously proposed distinguishing between tip and flat of the finger [31] or thumb [3], this new distinction develops this idea further and can be explored in future interface designs.

Finger Flexion: Finally, we note that finger flexion, previously proposed for in-air input scenarios [18; 37] may also be a viable and understudied modality for input on touchscreen smartwatches. In the static study, compared to the two other conditions studied, the side region offered a modestly wider range of comfortable input angles. In the dynamic study, it combined low task preparation times with low task execution times and correspondingly increased throughput. Error rates matched those from the more commonly studied flat finger touches [43] throughput. We suggest these benefits are likely due to the use of flexion and that future researchers and designers may be able to use this finger region to develop effective and comfortable input techniques for small devices.

7 INTERACTION TECHNIQUES AND APPLICATIONS

In this final section of this paper, we present the design of smartwatch interaction techniques and applications based on the data we present, and human-centered recommendations we derive, in this article. These largely adapt prior ideas with a particular focus on the side and flat touches, as these are less well studied than pair touches. We generated the following set of different input techniques.

Angle Menus: Menus which assign options to different angular ranges (like a pie menu) are a commonly proposed interface primitive for angular input [40], providing easy access to commands and placing limited memory load on users. In a *static* configuration, feedback about menu options should be displayed continuously (i.e., including when a user is not touching the screen) and targets should be at least 30° wide and triggered on finger release in order to support adjustment of touches prior to selection. *Dynamic* angle menus occupy similar regions, but are not shown by default – they are summoned by a long touch (or dwell) with either flat or side finger regions. Subsequently, a user can make angular movements and they show highlighting or a cursor depicting the current selection. They support a greater target density (down to a minimum size of 15°) as they are intended to be used only with interactive feedback.

Shortcuts: A variant on static angle menus, shortcuts do not involve any graphical cues and are triggered only by a rapid touch and release of an angled finger on the screen. They enable rapid execution of a small number of commands based on quick angled touches. As with static angle menus, 30° targets are a minimum; due to the lack of graphical feedback inherent in the technique, larger 45° target sizes are recommended.

Sliders: Rotation input is well suited to setting continuous or analogue parameters such as volumes, times or percentages [43]. We contribute to this idea by specifying comfortable 90°-120° ranges for input with different

Fig. 8. Demo applications. Left shows a user pointing to reply in a static angle menu in a message app using a flat touch. Center-left shows rotations of a side touch adjusting zoom in a map. Center-right shows selection of a brightness filter from a dynamic angle menu in photo app and right shows adjusting the brightness filter with a subsequent flat touch.

finger regions: 60° to 180° for side touches, 90° to 180° for flat touches and between 180° and 270° (and/or 0° and 90°) for two finger touches of the index and middle fingers. Data from the dynamic study also provides insight into the accuracy of final angles in this kind of input: reliable input can be achieved with a target size of 15°, and a drop in accuracy (to ~10% error rate) will result from 5° target sizes.

Flex–Swipes: Reflecting the potential of using finger flexion input on watch screens, we propose a novel variation on swipes. In contrast to commonplace straight movements, Flex-Swipes involve a screen touch with the side finger region followed by a rapid contraction or extension of the finger. This creates a unique input event composed of a large and rapidly rotating touch area in either clockwise or anti-clockwise directions. We propose this primitive as a rapid technique suitable for interface actions such as mode changes (e.g. like flipping pages) or large-scale, fixed quantity rotations, such as changing screen or content orientation by 90°.

Region–Aware Rotation: The distinctiveness of flat and side finger regions can enable different types of rotation input, allowing users to specify different parameters with by using different finger regions in the same interface. For example, a user might control the brightness or hue of smart lighting with continuous sliders in same user interface by accessing these functions with different finger regions.

7.1 Example Applications

We integrated these ideas into three example applications implemented on the same Sony smartwatches used in the studies. Figure 8 shows these prototypes. The first application was for viewing and light-weight editing of photographs. In addition to traditional touches to issue commands and swipes to navigate between images, Flex-Swipes in clockwise and counter clockwise directions resulted in matching 90° image rotations. A dynamic angle menu on the top and left of the watch could be summoned with a prolonged (>500ms dwell) side region touch. The menu featured four items, each occupying 18° of angular space and representing an image filter. After selection, the filters were adjusted using a flat touch to control a slider shown at the top of the screen.

A second prototype implemented Static Angle Menus in the context of a messaging app. A list of messages was displayed in the center/bottom-right of the screen, with a slim menu showing three options along both the left and top edges. Messages could be opened with a tap. Flat touches were used to select among reply, reply-all and forward commands along the top menu, while side touches could select from new, done and delete commands on the left. Rapid touches and releases led to immediate selection, or users could maintain their touch and make adjustments to the angle for high precision selection. Flex-Swipes were implemented as an alternative mechanism for rapidly issuing reply (clockwise) and forward (counter-clockwise) commands.

In the final map app, a canvas was displayed that could be translated with standard single finger drags. Region-Aware Rotation was used to access different functions. Rotations with the flat of the finger controlled orientation, while rotations with the side adjusted zoom. The map app also implemented three Shortcuts triggered by horizontal and diagonal side touches and vertical flat touches. The horizontal touch launched a search bar at the bottom of the screen (the most likely touch location) and the vertical touch a left side menu bar. Finally, the diagonal touch toggled between satellite and street view.

7.2 Application Study

To validate these designs, and make an assessment of whether the recommendations proposed in this paper can help developers create viable, comfortable interaction techniques for smartwatches based on angled or rotational input, we conducted a final qualitative study with 10 participants (six male, four female, mean age 23 (SD 2.04), all right-handed). These individuals had not participated in either prior study described in this paper and self-rated themselves as highly familiar with touch screen input (5/7), but not wearables (1.4/7). The study was based on procedures previously deployed to assess reactions to novel wearable interaction techniques [4; 30] and involved an experimenter performing a scripted demonstration of the input primitives available in each application, followed by the participants donning the watch, trying these out for themselves and commenting liberally.

We also asked a series of semi-structured interview questions about the usability attributes of each application that sought to ensure consistent coverage of issues including comfort, efficiency, learnability and memorability. We closed the study session by asking participants to comment on three general issues that appear across the whole set of techniques. These were: the contrast between static and dynamic rotations; the potential of rotation input to reduce the need for large on-screen targets and; the mapping of different inputs to different finger regions. The study took an average of 37 minutes to complete. The goal of this study was to complement the numerical, empirical ratings from the first two studies with direct capture of participants' reactions to the final designs and input techniques. We analyzed data in the study by recording all sessions and transcribing the comments verbatim. We then divided the transcriptions into meaningful semantic units (in the vast majority of cases, sentences) and performed an affinity process to cluster these comments into themes and categories. The semi-structured interview process, as it covered a specific set of topics and issues, provided an initial framing for these issues. We present key outcomes in terms of *comfort*, *performance* and *interaction design* below.

7.2.1 Comfort. We were particularly interested in comments relating to perceived comfort. These were positive, sometimes surprisingly so – for example, after using the mail app, P3 reported expecting the rotational "gestures will [induce] fatigue", but found this was not the case. Similarly, in closing comments, P2 noted that input expressivity is "surprisingly expanded" simply by "using different sides of [the] finger" via "tilting [the] wrist". Designing the inputs based on the findings from the initial studies helped achieve this. Expanding on his/her comments on the mail app, P2 indicated that activating the menu on the left of the screen with the side of the finger and top menu with the flat "matched [] expectation[s]", while P6 remarked that "diagonal touch with the side" of the finger (pointing from bottom right to top left) was "the easiest input" and should be assigned to very common functions. P6 qualified this comment by suggesting that rotations with the flat of the finger led to more "fatigue than other gestures" as the whole hand needed to be rotated. In more negative comments, P3 expressed reservations about input with the side of the finger due to the potential for "spoiling [his/her] nail" and its painting and decorations, while P1 noted that traditional single finger taps are "very comfortable" and questioned why rotational input is needed.

7.2.2 Performance. Participants were also generally positive about the input techniques in terms of their performance and effectiveness. Ten participants (across all three apps) remarked on the value of increasing the range of input available on a tiny screen. For example, after using the map app, P5 explained the rotational input lowered the need for a "messy screen with too many touchable menus" while still maintaining fast and convenient access to commands. P3 found the inputs in the mail app to be "easily expected and executed" and P10 saw value in using the flex-swipes as a generalized shortcut, suggesting they would be particularly "useful if [] customized". Two participants expressed doubts about the ability to perform rotational input in truly mobile scenarios – it was not "valid while moving" (P7). Learnability and memorability were closely related issues: most participants (15 mentions over the three apps) reported that although they needed "some time to be familiar" (P2) the rotational inputs were "not hard to learn" in "only a few minutes" (P3) in part due to their "consistency" (P10), "predictability" (P4) and, in the map app, the clear match between "menu bars and touch directions" (P2). There were concerns about whether older users could learn and memorize the inputs (5 participants), two participants doubted the discoverability of the techniques ("how can a user predict these gestures?" (P6)) and 9 participants, over all three apps, remarked on the departure of the techniques from standard two finger multi-touch operations, even though such traditional inputs were recognized as perhaps not "suitable for this tiny screen" (P6).

7.2.3 Interaction Design. Finally, participants also made various comments related to distinguishing or confusing the different inputs and their graphical presentation on the screen. In the gallery app, three participants felt that that "dividing the finger face into tool selection and [applying effects] is a very good idea" (P5) as they could be "naturally skilled" (P5) at differentiating between the two modes from the offset. Five participants felt the two rotational gestures in the map app readily supported input – P9 went so far as to claim that single finger rotational input was "easier than interacting with a smartphone map app". Some of the icons also supported the gestures: in the mail app, four participants reported expecting that the "rapid flex-swipe input would be connected to reply and forward shortcut[s]" (P9) because of the similarity of these motions to traditional arrow icons for these commands. On the other hand, some participants also reported confusion between the different input modes, such as the two rotational inputs in the map app (3 participants), or the speed threshold that should be exceeded to trigger flex-swipes (5 participants). This was in part due to the fact that the app designs somewhat intentionally lacked consistency and differed "in each application" (P8), so needed to be memorized separately. Unsurprisingly, participants identified that "apps need to be made with consistent input gestures" (P1). Finally, just two users remarked on the fat finger problem [34] and only for the map app. P8 put it as the "screen of smartwatch is too tiny. I want to see how it is rotated". This highlights the fact that rotational input occupies large portions of a watch screen, potentially exacerbating the inevitable occlusion of content caused by the touching finger.

7.2.4 Discussion. In sum, data from these participants suggests our guidelines can yield input techniques that are both comfortable and effective. Participants reported pleasant surprises and few complaints about the input primitives. We take this as an endorsement of the design recommendations presented in this paper. More generally, participants also responded positively to the increased expressiveness enabled by the techniques and anticipated that using them would be relatively easy to learn and remember, so long as they are deployed across a system in a coherent and consistent manner.

8 LIMITATIONS

A number of limitations impact this work. Firstly, we considered a narrow definition of comfort focusing on specifying yaw angles. Extending this to include other forms of input including pitch [25] or roll [33] is a logical next step. Secondly, the studies also took place in a lab setting and assessing the validity of the data in a more realistic real world environment involving activities such as walking or interaction while encumbered [6] would be a valuable extension to the current findings. Thirdly, while we use an established, practical, feasible and real-time system for detecting finger angles on smartwatches, based on Xiao et al. [43], there are a number of weaknesses to this approach. These include assuming that Xiao et al. [43]'s existing characterization of input performance holds for the current study. We note that while the close similarity between the smartwatch systems (in terms of touch sensor size, controller and underlying kernel modifications) suggest this is a reasonable assumption, we do also apply their algorithms to a new setting: input with the side rather that the flat of the finger. While the absence of differences in accuracy data in the static angles study suggest this algorithm performs well in this setting, future work should formally assess this. We also note that more advanced algorithms for touch angle sensing have been recently proposed [26]; determining if these offer improvements in our study setting is a next step for this work. This issue is particularly pertinent as the algorithm we employed has a known error in accuracy of detecting touches (with near flat finger pitch) of approximately 10° [43]. This means the results and design guidance we employ are valid only for systems that perform at this level of input accuracy. While it is represents a realistic, real time platform for developing interactive systems, a more accurate sensing algorithm (e.g., Mayer et al. [26]) may impact some of conclusions relating to target sizes reported in this article - a more accurate sensor may enable targets to be shrunk. Finally, due to the different study designs, comfort was assessed in different ways in each of the three studies in this paper. Consequently, variability in measurement instrument may serve as a confound to our conclusions. We note that the use of different comfort measurement techniques reflects a lack of well-validated instruments or approaches in this area. Future work should seek to establish robust standards for evaluating issues such as comfort of interaction techniques.

9 CONCLUSIONS

Comfort is an important quality of any input technique. This paper notes that many recently proposed interaction techniques for smartwatches imply a broad range of postures, poses and arrangements of the fingers, hands and arms. The comfort of these kinds of activity is an unknown quantity. This paper contributes initial data on this issue via two lab studies. The first gathers data from simple screen touches and releases using three finger regions (or poses) and eight input angles. Comfort data show strong variations with the different regions, clearly highlighting that user experiences vary considerably depending on both the finger regions used to make input and the angle of the input being made. Building on these findings, a second study looks at dynamic touches that move from one angle to another in the optimal ranges identified in the first study. Results show flat comfort ratings, and highlight variations in objective performance. The data from these studies can be used to reflect on the design of prior smartwatch input techniques and to inform future schemes. The paper closes by contributing design recommendations and interface examples that showcase how this could be done and by assessing how users react to these designs in a final study. The results indicate that the design recommendations support the creation of comfortable, effective interactions. We believe the data and design recommendations that form the core contributions of this paper will help researchers and designers create more objectively and subjectively usable smartwatch input techniques in the future.

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