DisplaySkin: Exploring Pose-Aware Displays on a Flexible Electrophoretic Wristband

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ABSTRACT
Mobile devices can provide people with contextual information. This information may benefit a primary activity, assuming it is easily accessible. In this paper, we present DisplaySkin, a *pose-aware* device with a flexible display circling the wrist. DisplaySkin creates a kinematic model of a user's arm and uses it to place information in view, independent of body pose. In doing so, DisplaySkin aims to minimize the cost of accessing information without being intrusive. We evaluated our pose-aware display with a rotational pointing task, which was interrupted by a notification on DisplaySkin. Results show that a pose-aware display reduces the time required to respond to notifications on the wrist.

Author Keywords
Smart Watches; Wearable Computing; Pose Aware Display; Flexible Displays; Organic User Interfaces.

ACM Classification Keywords
H.5.2 [Information Interfaces and Presentation]: User Interfaces---*input devices and strategies*.

INTRODUCTION
When performing every day activities, people are often interested in supplementary information. Am I on time? How close am I to my destination? How far have I run? The most common method we use to access supplementary information is retrieving a smartphone. Doing so, however, requires a significant interruption in a primary activity [20]. As a consequence, we must weigh the benefit of the information against the interruption it introduces. Explorations into head mounted displays address this issue by being always visible [8]. At the same time, these devices can be socially undesirable [32] and provide no simple method of dismissing the device.

It seems the ideal design space may be somewhere in between: devices that are easier to access than a smartphone, yet less intrusive than a head mounted display. Wrist worn devices are a candidate solution, one with a great cultural and social heritage. One of their primary features is that they can be brought in and out of focal attention with great ease; they are easily accessible to quick requests for information by the user. We therefore call this class of devices *glance-based* interfaces. Glance-based interfaces do not demand a user's focal attention, and provide information to the eyes quickly and only when needed.

TEI '15, January 15–19, 2015, Stanford, California, USA.

http://dx.doi.org/10.1145/2677199.2680596

Figure 1. DisplaySkin prototype.

With the continued growth in users' exposure to contextual information, we believe the design space of glance-based interfaces is becoming increasingly relevant. For these interfaces to be more efficient, it is important that information is available as quickly as possible and with minimal disruption of primary tasks. One issue with wrist worn devices is that their small display needs to be brought into the field of view, typically by lifting and reorienting the arm. In this paper, we propose a wrist worn device with a much larger display, one that is 320° degrees around the wrist, and is aware of the user's pose. Pose-awareness allows the device to provide information directly in the field of view, regardless of the orientation of the user's arm.

As an initial exploration of pose-aware displays, we designed *DisplaySkin*, a functional prototype electronic wristband (Figure 1). DisplaySkin includes a 7.2" thin-film flexible electrophoretic display that wraps around the circumference of the wrist. It also includes inertial sensors

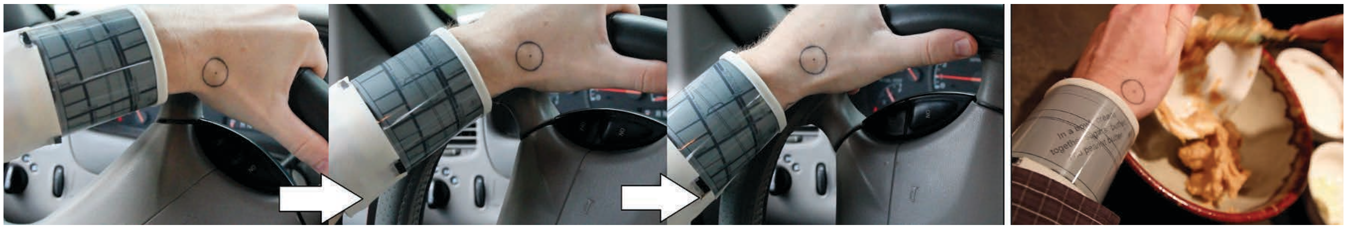

Figure 2. DisplaySkin prototype with pose-aware display.

that create a kinematic model of a user's arm and wrist. By wrapping a display around the entire wrist, DisplaySkin extends the angles from which pixels can be viewed. Using a kinematic model, DisplaySkin determines which areas of the display are visible and actively orients graphics to maximize readability (Figure 1). Figure 2 shows how combining a 320° visible screen with kinematic tracking enables DisplaySkin to provide pose-aware information in the context of everyday activities, such as driving or preparing food.

To investigate the potential benefits of pose-aware displays with DisplaySkin, we conducted an experiment that examined how fast users attend to supplementary information during a primary task. Results show that a pose-aware display can reduce the time required to respond to notifications that are secondary to a primary pointing task.

RELATED WORK

Wrist Worn Devices

A number of researchers have explored the design space of wrist worn devices. AugmentedForearm [23] is made from a row of four interconnected displays worn on the forearm. Facet [17] wraps six displays around the wrist, each acting as a window into an application. Users can rotate Facet to bring forward occluded applications, or can continually scroll to reveal virtual segments. Tarun et al. implemented Snaplet [34], a thin-film bracelet with a large display area. Snaplet's functionality changes according to its shape and the body part on which it is worn. WatchIt [25] and Abracadabra [11] expand the interaction space of wrist worn devices beyond the display using touch and in-air gestures, respectively. With Duet, Chen et al. [4] explored joint interactions with a smartwatch and a smartphone.

In addition to recent wrist worn products [9,24,26,30], Plastic Logic demonstrated a prototype smartwatch. Their prototype also used a flexible electrophoretic display, wrapped over a small portion of the wrist [26].

On Body Interaction

Rather than *attach* a device to the body, some researchers *integrate* a device with the body by interacting directly on the skin. Rekimoto explored tapping on skin for mobile interactions, leveraging skin's direct tactile feedback [29]. Nakatsuma et al. [22] detected finger position on the back of the hand using a combination of piezoelectric and infrared sensors. Makino et al. [19] detected the force and linear position of a finger between two infrared sensors placed on the arm. With Skinput, Harrison was one of the first to use skin for *both* input and output [13]. Skinput used bio-acoustic fingerprinting to locate taps on a user's forearm, but also included a body-mounted pico-projector for direct feedback. OmniTouch [10] augmented users with a projector and a Kinect sensor, enabling multi-touch interactions on everyday surfaces, including the user's own arms and hands. Harrison et al. extended this work with Armura [12], which tracked both the hands and arm posture. With Armura, users could control interfaces with arm and hand gestures.

Body Pose as Input

In addition to designing interactions *on* the body, a number of papers explored designs *with* the whole body as input. For example, Chen et al. proposed a number of new paradigms using the body as an interactive space [5], such as navigating data by moving mobile devices relative to the body. In addition, he demonstrated how users could create a mnemonic map by storing and retrieving information at chosen locations on and around their body.

Several areas in HCI leverage body pose: for rehabilitation [28], low-cost 3D modeling and rigging [43], and tracking daily activities [2]. Some solutions to detect pose embed sensors directly into clothing. Strohmeier et al. [33] put stretch sensors into sleeves to detect basic wrist motion and Gioberto et al. [7] created stitching patterns for conductive thread that estimate joint angles. The most common methods for measuring pose, however, are depth-sensing cameras [21], a series of inertial sensors [42], or by tracking infrared markers with an array of cameras [37].

Dynamic Image Rotation

Since the early 90s, researchers have suggested rotating content with the orientation of its display [35]. Today's mobile devices automatically show content in portrait and landscape modes, using accelerometers specifically included for this purpose. But if a device relies on its display orientation alone, it may make inaccurate assumptions about a user's perspective. For example, users often disable this feature when lying down [16]. Cheng et al. [6] addressed this problem by using the orientation of a user's face to adjust the orientation of a display. Their approach, iRotate, requires a direct view of the face, and like most mobile devices, it only transitions between fixed

Figure 3. Wrist worn devices. Left: Bracelet watch by Capt & Freundler (1813) [38]. Right: Samsung Galaxy Gear smart watch (2013) [30].

orientations. In contrast, Wilfinger et al. [41] used accelerometer data to smoothly rotate content on steering wheel displays.

DESIGN RATIONALE

There are varying accounts describing the invention and popularization of the wristwatch [15]. Early advertisements for wristwatches show how the bicycle and automobile were important factors; the ads tout how motorists could more easily read the time while operating a vehicle [1]. Other accounts describe military officers who found it impractical to use a pocket watch while also riding a horse and wielding a pistol. In WWI, the British Army commissioned one of the first mass-produced wristwatches because their soldiers required fast access to timepieces for coordinated attacks [39]. A common design theme runs through these differing origin stories: one of convenient access. Inspired by wristwatches, the main design goal for DisplaySkin is to allow users to more easily access information in a way that supplements their primary activity.

Designing for Non-Focal Attention

Wristwatches have come a long way since then. Indeed, wristwatches with the power of full-fledged computers are now becoming a reality in the marketplace. At the same time, wrist worn devices and computers have different motivations and we typically engage with the two classes of devices in very different ways. Designers usually assume that a computer is the primary focus of attention, the sole object a user is interacting with over an extended period of time. The design of wristwatches is quite the opposite. They are not assumed to be the focus of attention, instead supporting fleeting glances of secondary or contextual information: knowledge that complements a primary task. This means that the effectiveness of a wrist worn device should be weighed against its impact on a primary task. We believe that when designing smarter wristwatches, one should not be tempted to naively copy methods proven for standard computers. Instead, we suggest a focus on enhancing the existing affordances of the wristwatch.

Designing for Visibility

The form factor of most wrist worn devices has not significantly changed over the past two hundred years, yet the size and placement of the display is a key parameter of visibility. For example, Figure 3 shows one of the first wristwatches ever made (1813) [38] beside a Samsung smartwatch (2013) [30]. Despite the difference in their underlying technologies, their displays are in the same fixed location. This constraint limits the angles from which the display can be viewed. A flexible display, on the other hand, can be wrapped around the wrist, providing a continuous display surface with pixels always in view.

Designing for Body Pose

Our primary concern was how to compensate for the occlusions of display area that commonly occur in day-to-day activities. To address this, we propose measuring the configuration of the user's arm in relation to the rest of the body and dynamically moving information onto an area of the display that is visible. As such, a pose-aware display re-orients its content towards the user, rather than requiring the user to reorient their body towards the device. Our pose-aware display consists of two elements: a flexible display and a kinematic model of the body. By wrapping a display around the wrist, DisplaySkin has a surface with pixels always visible, independent of the rotation of the arm. By measuring the configuration of the user's arm in relation to the rest of the body, DisplaySkin can dynamically move information onto this area of the display that is visible to the user (see Figure 4).

DisplaySkin also dynamically reorients text and other content, correcting for perspective effects. This can reduce

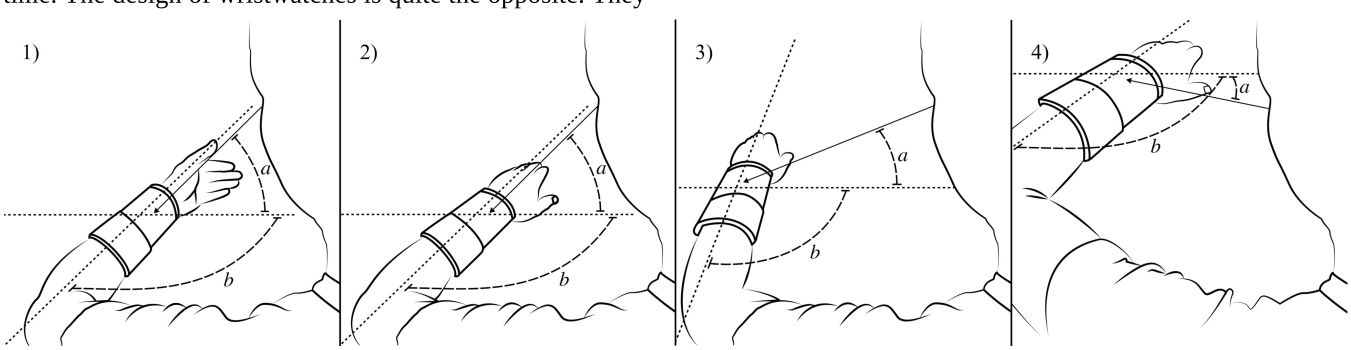

Figure 4. The kinematic model provides DisplaySkin with the angle between a user's eye and the device (*a*). DisplaySkin uses this angle to present information on visible area of the display. The model also provides the orientation of the device relative to a user's body (*b*), which is used to align the content horizontally (similar to Wilfinger et al. [41]).

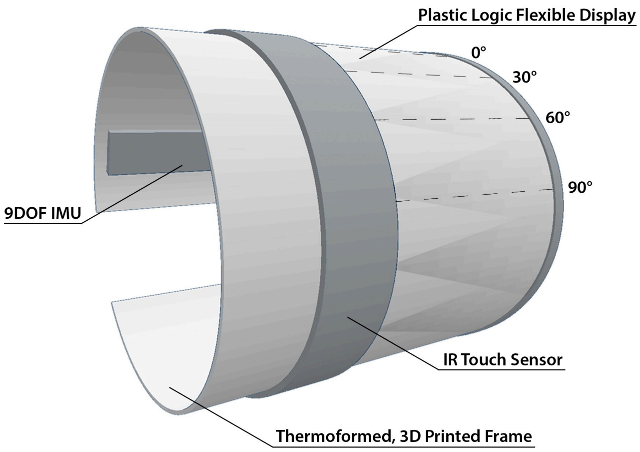

Figure 5. DisplaySkin hardware schematic.

interruption times because it improves the readability of any text displayed on the device [40]. With a pose-aware display, interfaces can be presented with a fixed perspective, regardless of how the arm is oriented. Similar to Wilfinger et al. [41], a map's north could remain upright, independent of hand orientation (Figure 2).

We also envision that future glance-based interfaces will have a degree of ambient awareness to better provide contextually relevant information. Our focus in this paper, however, was to make glancing at a device easier and less disruptive. Although a fully contextually aware device lies outside the scope of this paper, we hope our sensing platform guides future work in the area.

IMPLEMENTATION

Figure 5 illustrates DisplaySkin's components. DisplaySkin uses a flexible electrophoretic display from Plastic Logic [27] with a resolution of 354 by 944 pixels. The display is 6.5" long and 3" wide (7.2" diagonal).

Device Assembly and Form Factor

The 0.2mm thick display was inserted into a flexible 1.5mm thick 3D printed ABS frame. Once inserted, the entire device was heated and molded into a cylindrical shape. The final form factor of DisplaySkin is rigid enough to stay wrapped around the arm, yet sufficiently flexible to open and close comfortably. For added stability, a magnetic snap holds DisplaySkin in place.

Kinematic Tracking

To create the kinematic model, DisplaySkin uses two Inertial Measurement Units (IMU). One is worn around the user's upper arm and one is integrated in DisplaySkin itself. Each IMU contains a 3-axis gyroscope, a 3-axis accelerometer, and a 3-axis magnetometer. Two Arduino boards collect the data, and a sensor-fusion algorithm [18] calculates the absolute orientation of each IMU.

We use these headings to create a direct, forward kinematic model of a user's arm. The model treats a user's shoulder as the base of an open kinematic chain with two links. Each IMU represents one element in this chain and is considered a rigid body [31]. With this, we calculate the position and orientation of the user's wrist relative to their shoulder. The model assumes that a user's face is in a fixed position relative to their shoulder, an assumption that is sufficiently accurate to calculate an angle and rotation offset between the forearm and face (Figure 4). A single gyroscope would be sufficient to detect simple rotations of the arm (compare Figures 4.1 and 4.2). A kinematic model, however, is required to detect differences between more complex changes in pose (Figures 4.3 and 4.4).

Touch Sensing

To the best of our knowledge, there is no technology that can track multiple touches on the thin, flexible, and curved conditions of electrophoretic displays. As a result, we designed a sensor using infrared (IR) diodes, inspired by SideSight [3].

We placed an array of IR diodes over the bezel of the display. The diodes act as both photoemitters and phototransistors (emitting and sensing IR light, respectively). These diodes are controlled by a separate Arduino microcontroller. When a finger comes in close proximity of the display, it is illuminated, and the reflection of IR light is detected. Touch points are calculated with a custom blob-tracking algorithm. The y-position of a touch is based on blob location, while the x-position is inferred by its size and intensity.

Software

DisplaySkin's display driver is based on Holman et al.'s Flexkit [14], which runs on Plastic Logic's Hummingbird Z3. Flexkit allows DisplaySkin to run at high frame rates on the inherently slower electrophoretic display.

The two Arduino boards preprocess all the sensor data. A laptop receives the IMU data and creates the kinematic model in a Processing application. A separate Processing application consolidates the touch data and the kinematic model and updates the display. The inter-process communication was implemented in Open Sound Control.

USER STUDY

To understand how pose-aware displays benefit glance-based interfaces, we evaluated the effects of display occlusion on information retrieval. We measured participants' ability to quickly acknowledge notifications presented on DisplaySkin, while they were simultaneously engaged in a different primary task.

In this evaluation, we compared a pose-aware display to a static display (placed on the top of the wrist). Instead of comparing the two in extreme situations, we maintained ecological validity by focusing on the more interesting edge case of partial occlusion. We believe these scenarios would

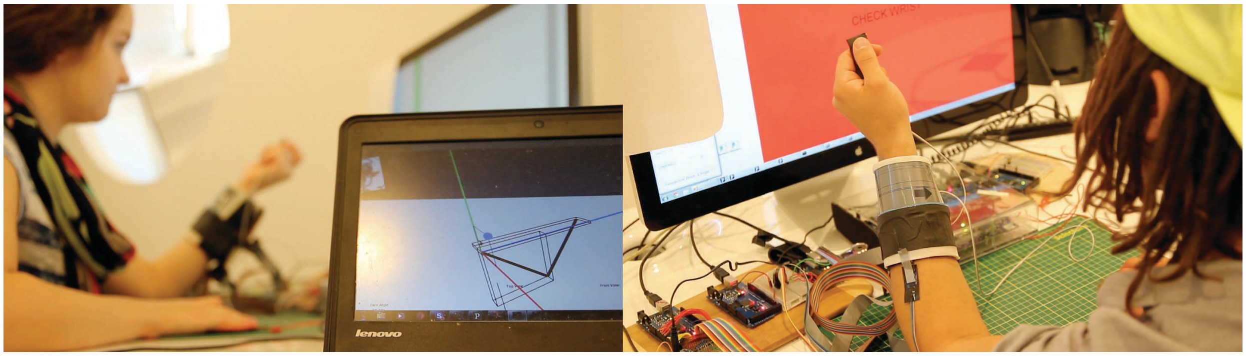

Figure 6. Experimental environment. Left: Live view of kinematic tracking. Right: Participant is interrupted and must acknowledge arrow on DisplaySkin.

reveal both the positive and potential negative aspects of a pose-aware display.

Task

As a primary task, participants performed a targeting task, similar to a one-dimensional Fitts' law pointing test. Two bars appeared on a desktop monitor and spanned the height of the screen. The bars were fixed in width and were varied in amplitude between conditions. Participants were asked to move a cursor between the two targets as quickly and accurately as possible. They controlled the cursor's horizontal position with the rotation of their left hand.

As a secondary task, participants performed an acknowledgment task on DisplaySkin. Upon completing a random trial of the primary task, the participant was interrupted by a notification: the monitor flashed red. Upon such notification, participants were instructed to look at DisplaySkin, find an arrow, and swipe in the direction indicated (Figure 6, right). Once the notification was acknowledged, participants immediately returned to the rotational targeting task.

By asking the participants to perform a task with wrist rotation, we were provided with a wide variety of wrist angles. This, in consequence, allowed us to control the level of occlusion of the top of the wrist at the moment when a notification occurred. In addition, the demands of the task required the participants' full concentration, ensuring they could not plan for interruptions.

Conditions

We used two independent variables: display type and angle. The two display types were *static* and *pose-aware*. The angles were 0°, 30°, 60°, and 90°. Figure 7 shows the position of the arm for each condition, while Figure 5 shows the corresponding position of the target on the display. In the pose-aware condition, the arrow was dynamically placed in the participant's field of view. In the static condition, the arrow was located on the top of their wrist, the standard position of a watch face. The different angles constituted varying degrees of occlusion of the arrow.

Controlling Wrist Angle and Hand Position

During a trial, the participant's left elbow and right hand were in a fixed position. The participant controlled the targeting task with their left hand and they held their right hand in a fixed position. This allowed us to specify the angle of the left forearm when the interruption occurred, as well as ensuring that the distance between the right hand and the display was consistent between participants.

Measurements

We recorded two dependent measures: homing time and resume time. *Homing time* is the time from the moment of the interruption until the participant touched the surface of DisplaySkin. *Resume time* is the time between completing the swipe to re-engaging with the targeting task, as indicated by a click on the same target that prompted the interruption.

Experiment Design

We used a 2x4 factorial within-subject design with repeated measures. Our factors were: *display type* (static and pose-aware), and *wrist angle* upon notification (0°, 30°, 60°, and 90°). Each participant performed 8 trials of the acknowledgment task per combination of factors, for a total

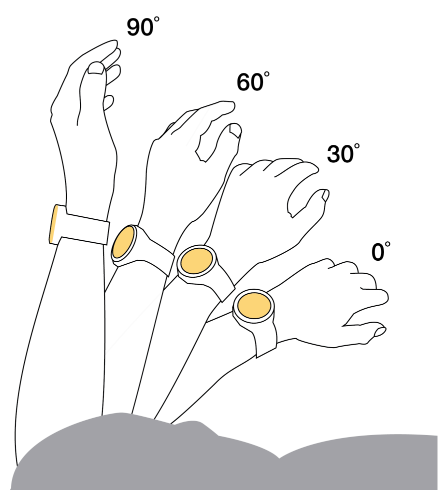

Figure 7. Wrist angles investigated. Watch face visibility indicated in yellow.

of 64 trials. Condition order was countered-balanced between participants. The experiment lasted 40 minutes, including practice. Participants practiced with each display type until they achieved less than 10% improvement between trials. Participants clicked between the vertical bars for a total of 384 targeting trials. The trials were segmented into blocks of 6, grouped by target distance (each target distance corresponding to a wrist angle). There was one interruption within each block of the targeting trials. It occurred randomly when a participant clicked on the target bar that corresponded to the desired wrist angle.

Participants

The experiment was conducted with 12 participants (9 male, 3 female) between the ages of 17-29. Most participants were right handed (9/12) and only a few currently wore a wristwatch (3/12). All participants had some familiarity with touch gestures, e.g., on a smartphone or tablet. They were paid $10 for their participation.

Apparatus

Aside from DisplaySkin, we needed additional hardware to perform the experiment. We instructed participants to place their right hand on a capacitive sensor that ensured consistent starting locations for homing locations. To select targets in the primary task, participants pressed a small push button that they grasped with the same hand (left) with which they wore DisplaySkin.

Hypotheses

We hypothesized that the pose-aware display would have faster homing times than the static display (*H1*). We predicted that participants would be able to home to the wrist faster when the arrow was dynamically placed in their field of view. We also hypothesized that, for the static display, larger wrist angles would result in slower homing times, but we would not see this effect with the pose-aware display (*H2*). We hypothesized that participants would have shorter resume times in the pose-aware display condition (*H3*).

As a control, we expected that targeting times in the primary rotational pointing task would not significantly differ between display types (*H4*), and that larger target amplitudes would result in longer targeting times (*H5*).

RESULTS

For the secondary acknowledgement task, we analyzed the collected measures by performing a repeated measures ANOVA using *display type* (2) x *wrist angle* (4) on homing time and resume time. Table 1 outlines the means and standard errors for homing and resume times.

For homing time, the analysis showed that *display type* was a significant factor ($F_{1,11}$=67.99, $p < 0.001$), with the pose-aware display resulting in shorter times than the static display. We also found a significant interaction effect between *display type* and *wrist angle* ($F_{3,33}$=3.29, $p < 0.05$).

	Homing Time		Resume Time	
	Static	**Pose-Aware**	**Static**	**Pose-Aware**
Overall	1.84 *(0.04)*	1.5 *(0.02)*	1.75 *(0.02)*	1.69 *(0.03)*
0°	1.69 *(0.04)*	1.55 *(0.03)*	1.74 *(0.04)*	1.90 *(0.05)*
30°	1.82 *(0.07)*	1.52 *(0.03)*	1.60 *(0.04)*	1.85 *(0.07)*
60°	1.88 *(0.10)*	1.46 *(0.04)*	1.81 *(0.05)*	1.42 *(0.05)*
90°	1.90 *(0.07)*	1.47 *(0.03)*	1.88 *(0.06)*	1.59 *(0.03)*

Table 1. Mean *(s.e.)* homing and resume times in seconds.

With respect to resume time, we observed a main effect of *wrist angle* ($F_{3,33}$=5.14, $p < 0.05$). Pairwise post-hoc tests, with Bonferroni corrected comparisons, revealed that 0° was significantly different from 90°. The analysis also showed an interaction effect between *display type* and *wrist angle* ($F_{3,33}$=15.12, $p < 0.001$).

For the rotational pointing task, we analyzed the movement times by performing a repeated measures ANOVA using *display type* (2) x *target amplitude* (4). The analysis showed that *target amplitude* was a significant factor ($F_{3,33}$=219.48, $p < 0.001$). The analysis did not show a main effect of *display type*.

DISCUSSION

Our results suggest that pose-aware displays reduce interruption times in interactions with a wrist mounted display when attending to a primary pointing task.

As hypothesized, our pose-aware display obtained significantly faster homing times than the static display (*H1*). We believe this result is because the pose-aware display presented the arrow directly in the participant's field of view, regardless of their wrist angle when the notification occurred. In addition, we confirmed our hypothesis (*H2*) that there would be an interaction between *display type* and *wrist angle*. With the static display, larger angles resulted in larger homing times.

Although we did not see a main effect of *display type* on resume times *(H3)*, we observed a significant interaction effect between *display type* and *wrist angle*. We believe the interaction effect can be explained by the different strategies we observed participants employ for small and large angles. When faced with a small angle (little to no occlusion), participants would keep DisplaySkin still and touch their left wrist with their right hand. As a consequence, their left hand remained in an ideal position to resume their primary task. Furthermore, larger angles (with larger amounts of occlusion) compelled participants to rotate their left wrist when homing with the right hand. With their left hand now in a different pose than at the start, participants were slower to resume the task.

In the pose-aware condition, participants typically swiped with a bimanual gesture. We observed that participants often let their left and right hands meet in the middle, a comfort permitted since DisplaySkin did not need to be at a specific angle. Resume times were therefore faster for the larger angles, and homing times were more efficient throughout. Swiping in the pose-aware condition was more efficient, since the right hand traveled a shorter distance to meet the left hand and there was no need to explicitly rotate the left wrist to re-orient the arrow.

Somewhat surprisingly, we found that in the 0° condition, the pose-aware display had faster homing times than the static display, a scenario where performance should be equivalent. We believe this difference is due to the dynamic nature of the pose-aware display and these differences in acknowledgement strategies. Even though the target appears at the same place, it adjusts position during the interaction: the swiping motion is more efficient when the arrow remains at an angle that is easier to reach.

In the pose-aware conditions, it appears that the 60° angle resulted in the shortest times for both homing and resume times. The result suggests that users may be naturally inclined to touch at that angle of the wrist for interactions that are not constrained by a fixed target. This result might be relevant to the design of wrist worn devices that are not pose-aware. There may be a benefit to having the display and interaction area slightly rotated facing the body, away from the 0° position, and towards the 60° position.

Although the targeting task was not the focus of this experiment, we conducted a statistical analysis of the task to ensure that the conditions were consistent across both display types. We confirmed our hypothesis that movement times did not differ between display types (*H4*) and larger amplitudes resulted in longer times (*H5*). Even though non-significant difference is not equivalence, these results are enough to suggest that the participants' focus was on the primary task.

FUTURE DIRECTIONS

Our prototype was tethered to a dedicated driver board because flexible displays are still a new technology. When given the opportunity to explore DisplaySkin before the experiment, some users noted that the cables occasionally restricted their movement. Later, they commented that for the more limited motion required in our experiment, the cables did not concern them. In the future, we aim to reduce these cables through miniaturizing the driver boards.

In our current prototype, our forward kinematic model requires users to wear, not only DisplaySkin, but also a small (8 x 36 x 2mm) secondary IMU on their upper arm. Future research in tracking algorithms may allow us to create an inverse kinematic model to remove this IMU.

One of the results revealed during our study is that there are interaction effects between wrist angle and display type; since the pose-aware display adjusts to the users movement, the effects of arm rotation are corrected for. This result presents an opportunity for further study into the ergonomics of wrist interactions.

Our tracking technology was primarily implemented to support a pose-aware display. At the same time, we feel it is a strong platform for building future context aware applications for situations that would greatly benefit from a pose-aware display. For example, to understand eating habits, one might create an application that records how many mouthfuls a meal was divided into and at what frequency the mouthfuls were consumed. A golf player could use an application that shows how hard the golf ball was hit and how well the swing was executed. The kinematic model might also learn which instruments its user plays and switch into a sheet music library, or recording mode, when the user is playing. Identifying a driving pose becomes straightforward as well, making it easy to automatically supply the driver with relevant information, such as a map (Figure 2).

In addition to our kinematic tracking, we also believe that there might be strong synergies with other sensing technologies such as the MYO [36] or Rekimoto's GestureWrist [29].

CONCLUSION

In this paper, we presented DisplaySkin, a prototype pose-aware display with a large 320° cylindrical display surface. Our prototype is the first interactive wrist worn device to adjust its display to the user's body pose. DisplaySkin is also unique in regards to its degree of curvature, flexibility, and display size.

To evaluate whether a pose-aware display helps users access information more efficiently, we designed an experiment in which users performed a rotational pointing task that was interrupted by a task on the wristband display, at varying angles. Results suggest that pose-aware displays reduce the time taken to acknowledge the notification, minimizing the overall interruption. Our results also suggest that some areas on the wrist might be more natural to touch than others and that pose-aware displays may be a useful method of exploring ergonomics of body-worn devices.

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