Sensing Posture-Aware Pen+Touch Interaction on Tablets

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ABSTRACT

Many status-quo interfaces for tablets with pen + touch input capabilities force users to reach for device-centric UI widgets at fixed locations, rather than sensing and adapting to the user-centric posture. To address this problem, we propose sensing techniques that transition between various nuances of mobile and stationary use via postural awareness. These postural nuances include shifting hand grips, varying screen angle and orientation, planting the palm while writing or sketching, and detecting what direction the hands approach from. To achieve this, our system combines three sensing modalities: 1) raw capacitance touchscreen images, 2) inertial motion, and 3) electric field sensors around the screen bezel for grasp and hand proximity detection. We show how these sensors enable posture-aware pen+touch techniques that adapt interaction and morph user interface elements to suit fine-grained contexts of body-, arm-, hand-, and grip-centric frames of reference.

CCS CONCEPTS

• Human-centered computing → **Ubiquitous and Mobile**

KEYWORDS

tablets; sensing; grip; posture; electric field sensing; pen + touch

ACM Reference format:

Yang Zhang, Michel Pahud, Christian Holz, Haijun Xia, Gierad Laput, Michael McGuffin, Xiao Tu, Andrew Mittereder, Fei Su, William Buxton, and Ken Hinckley. 2019. Sensing Posture-Aware Pen+Touch Interaction on Tablets. In *2019 CHI Conference on Human Factors in Computing Systems Proceedings (CHI 2019), May 4–9, 2019, Glasgow, Scotland, UK.* ACM, New York, NY, USA. 14 pages. https://doi.org/10.1145/3290605.3300285

Figure 1A-G. Our system senses nuances of mobile *vs.* stationary use, and morphs the UI accordingly. See text for details.

1 INTRODUCTION

The mobility of tablets affords interaction from various user-centric *postures.* Yet current tablet interfaces often assume a *device-centric* perspective. Controls inhabit fixed positions at the margins of the screen, and remain unaware of transitions between postures—much less the subtle nuances of these reference frames and contexts of use. A device-centric UI design requires the user to adapt their behaviors to the layout of the interface on the tablet, rather than having the tablet adapt its behaviors and controls to how the user is actually holding and using the device.

Sensing this missing context affords *Posture Awareness.* Posture-Aware Interfaces sense and transition between various egocentric frames-of-reference, including body-, arm-, grip-, and hand-centric. While some aspects of this approach appear in previous work (e.g. [2, 18, 41, 74, 80]), automatically sensing and transitioning between a plurality of egocentric reference frames—as well as exocentric *world-* and *device*-centric reference frames, when appropriate—offers a key contribution of our system.

Our Posture-Aware Interface morphs to a suitable frame of reference, at the right time, and for the right (or left) hand. This affords both one-handed and bimanual pen+touch interactions for tablets. Each hand plays a distinct role (in its own local reference frame) to *support* the tablet and *interact* with the screen [80] via touch, or the pen. As we move down the kinematic chain [30, 80]—from the body to the joints of the elbow, wrist, and hand—the frame-of-reference relevant to a context becomes more specific. Our system senses and transitions between these multiple frames-of-reference, in a manner contingent on posture.

For example, Fig. 1 shows some contexts sensed by our system. Grasping the tablet summons *Thumb Tools* to a grip-centric location nearby, such as the left (Fig. 1a) or bottom (Fig 1b). Putting the tablet flat on a desk reverts to the *Default Tools*, at a device-centric position near the upper right (Fig. 1c). Planting the preferred hand on the screen to write automatically orients miniature *Palm Tools* (Fig. 1d) to a hand-centric location nearby. We also sense laying down the pen to reveal hidden settings (Fig. 1e). A two-finger touch splays out *Fan Tools* for bimanual pen+touch (Fig. 1f). But if the user instead invokes them with the preferred hand, the Fan Tools splay out in the opposite direction and adapt their behavior to suit one-handed use (Fig. 1g). For each of these states, animated transitions help make clear how the system responds to shifting contexts, and when.

Our contribution is integrative, taking some elements explored previously (such as thumb controls [26, 63], or accommodating multiple grips [80]), and unifies them through interaction techniques with automatically sensed transitions in look & feel of the interaction. Thumb controls, for example, are a particular use-case supported by previous work—yet often only in a fixed manner of use, with static controls that must be managed by the user. But in our work, (1) the particular contexts where thumb controls should appear, or disappear, or move to a new grip-location, are automatically sensed; and (2) the techniques therefore also support transitions to other styles of use when users change how they hold the tablet, or otherwise shift contexts. Our strategies for moving between handheld tablet use, versus a supporting surface with full bimanual interaction, offer one example of how our work puts this into action.

Taken as a whole, then, we contribute the following:

- *Posture-Aware Interfaces* that sense and transition between body-, arm-, grip-, and hand-centric frames of reference, for pen/touch interaction on tablets;
- Realized via a pragmatic combination of three sensors:
  - raw capacitance touchscreen images for detection of the palm (or the pen itself) when placed on the screen;
  - inbuilt inertial sensing for detecting the angle of the display, or tilting movements of the entire tablet;
  - peripheral electric field sensors on the bezel of the device for grip and hand/forearm proximity sensing;
- With example techniques that illustrate how a pen & touch interface can morph its UI elements and interactive behavior accordingly;
- And preliminary user feedback that shows advantages as well as some remaining challenges of our approach, such as the need for automatic adaptations to feel stable and predictable (rather than, for example, distracting by responding immediately to every minor hand motion).

Our work reveals how "mobile vs. stationary use" [38] is far from a simple dichotomy: many aspects of grip, handedness, and posture are required to gracefully degrade bimanual pen+touch to the varied usage contexts manifest on tablets. Our techniques show that sensing these qualities opens new possibilities for touch (and pen) interfaces that go beyond device-centric approaches, letting the user work effectively from transient postures.

2 RELATED WORK

We address core user interface challenges for tablets, including round trips, divided attention, biomechanical comfort, and hand occlusion. Our approach considers these as problems (at least in part) of insufficient context that could be sensed via raw capacitance images, tilt and motion, grip, or electric field—with emphasis on pen+touch interactions.

2.1 Round Trips, Attention, Comfort, & Occlusion

Most interfaces divide real estate between a *Workspace*, which features user content, and *Tools* (palettes or menus) which typically occupy the outer edges of the screen. On direct-touch devices, round-trips between Workspace and Tools are monotonous, require a lot of hand movement [23], and demand *divided attention* [51]. This also prevents the user from leaving their hand planted at an advantageous position and orientation on the screen. For example, artists tend to rotate artwork frequently as they work [24], to suit the biomechanics of crafting pen strokes with comfort and skill. Moving the preferred hand far away to acquire Tools disrupts focused attention and flow [6, 20], and also runs counter to the UI principle of *location-independence* [64].

Occlusion presents another challenge. Placing controls near-to-hand is desirable—yet if too close, the hand blocks them from view. Much work on occlusion-avoidance focuses on the preferred hand [25, 59, 78, 79], although Vogel et al. do study one bimanual gesture [79]. But tablets afford many postures. Users can employ either hand, or approach an angled tablet from various directions [59]. Our work uses electric field sensing to add awareness of hand proximity and the forearm angle associated with each touch.

2.2 Roles of the Hands During Tablet Interaction

The user must juggle strategies to work-around these limitations. For example, users frequently adjust grips or usage postures for comfort [40, 59, 80]. Many tablet grips involve both hands in distinct roles [30]. The nonpreferred hand can *support* the device, or *interact* with it—or at times both—with the forearm, palm, and fingers occupying distinct roles in a kinematic chain [30, 80]. The preferred hand may touch the screen, articulate pen strokes, or help support (grip) the device as well. But the burden falls on the user to manage the layout of fixed, device-centric user interface controls across the oft-shifting postures of the hands and device.

Efficient controls can be designed with such grips and usage patterns in mind. BiTouch and BiPad [80], SPad [26], and Thumb + Pen [63] provide nonpreferred-hand thumb controls to swipe through menus and switch modes, in support of touch or pen inputs in the main Workspace of the application. Other interaction design strategies, such as swipe and pinch touch gestures—or command strokes drawn with the pen [47, 50, 92]—allow users to directly invoke actions on the workspace. But gestures can only support a few key actions effectively.

Our work focuses on the complementary strategy of *posture awareness*, and illustrates how this enhances other approaches via sensing. For example, our Thumb Tools show how to make thumb controls posture-aware—including how they automatically come and go, or transition to different manifestations in other usage contexts.

2.3 Sensing Techniques

Buxton [13] argues that much of the complexity that people experience with technology stems from the burden of explicitly maintaining missing state. This consists of missing context [68] that comprises the implicit *background* of the interaction. However, grasping, manipulating, and touching screens—all explicit *foreground* actions—feel so routine that one rarely thinks of awkward or inconvenient tablet interactions in such terms. Yet sensing and responding to fine-grained shifts of hand placement, grasps [18, 19, 61, 74, 83], and device micro-mobility [54, 88] show promise. Our work adopts this background perspective and focuses on sensors with pragmatic potential for consumer tablets.

2.3.1 Raw Capacitance Touchscreen Image Sensing

Early tabletops relied on image recognition techniques [12, 21], leading to many examples of rich input, such as to detect objects [46, 75, 76] placed on the screen, or to sense additional parameters of touch [10, 15, 35, 84]. But recently, touchscreen capacitance images have become available on many mobile devices, spurring new work. For example, the palm can serve as a distinct input modality [52, 70] to augment standard multi-touch on smartphones. Bodyprint [43] and CapAuth [31] use ear-prints and palm-prints, respectively, for identification. Capacitance images also allow estimating the 3D pose of the finger during touch [87]. While some work explores rich image sensing for tablets [3, 5, 67] or on a touch-sensitive mat [76], very little considers tablets in mobile postures [82].

Several papers have explored hand and contact-shape recognition as an input channel [15, 58], including the extension of specific fingers to trigger modes during unimanual pen + touch input [14]. These approaches propose new gestures—that is, *foreground* actions triggered by intentionally shaping the entire hand—geared towards larger, non-mobile touch surfaces. By contrast our techniques (such as the Palm Tools, described later) are geared towards tablets, and focus on *background* sensing of the normal preferred-hand resting behavior of the palm to bring up tools at an appropriate, near-to-hand location.

2.3.2 Tilt (Inertial Motion) and Grip Sensing

Inertial sensors such as accelerometers and gyros are ubiquitous on smartphones and tablets, to support context sensing [68] techniques such as automatic screen rotation [36]. Likewise, grip offers a promising sensing channel to adapt mobile interactions to particular contexts of use [74] such as to detect which hand grasps a mobile device [28, 33, 83]. On tablets, grip sensors have been used to automatically place graphical keyboards at a suitable location [19], as well as to sense shared use [88]. These efforts hint that grip and motion offer complementary sensing channels, perhaps best used in combination [18, 40].

2.3.3 Above and Around-Screen Sensing

Research has explored hand movements above and around displays. While such non-contact gestures can be used to issue commands or manipulate parameters [11, 17, 57], we focus on them as implicit channels for context sensing.

Pre-touch (e.g. infrared sensing on a tabletop [2], or self-capacitive touch on a mobile [41]) affords sensing hands proximal to the display. This can be used for early detection of impending touch [85], reaching direction [2], or to support an “ad-lib interface” that adjusts user interface controls to various gripping contexts [41]. Our work investigates a pragmatic approach to detect both grip and hand proximity in the same sensor, via an electrode ring integrated with a tablet’s screen bezel for peripheral electric field sensing.

2.4 Pen and Touch

There has been much work on pen and touch [9, 27, 32, 38, 91], but relatively little has explored how to adapt (or

Ref. Frame	**Foreground** *(Explicit Actions Required)*	**Background** *(Posture Awareness Sensed)*
World	• Enhancing Pen-and-Tablet [71] *Tilt tablet to go through layers*	• Mobile Sensing [36] *Display auto-rotation relative to gravity*
Device	• SideSight [11] *Gesture around edges of a mobile* • Continuous Int. Space [57] *Lift above-screen to reveal docs* • Air+Touch [17] *Raise finger for commands*	**Default Tools: Put Tablet Down Flat for Stationary Use** • iGrasp Adaptive Keyboard [19] *Keyboard reverts to standard layout if not gripping*
Grip	• BiTouch and BiPad [80] *Interaction zones for multiple grips* • SPad [26], • Thumb + Pen [63] *Thumb widgets afford held tablet*	**Thumb Tools** • Pre-Touch (ad-lib interface) [41] • iGrasp Adaptive Keyboard [19] *Split or reposition keyboard via grip*
Pen / Cursor	**Pen: Lay Down to Customize** • Hover Widgets [29] *Pen gestures above-screen* • Sensing Tablet+Stylus [40] *Touch with pen-in-hand for menu*	**Pen: Lay Down & Imprint Phantom in Mobile Postures** • Tracking Menus [23] *Menu follows pen hover movements* • Enhancing Pen-and-Tablet [71], • Sensing Stylus+Tablet [40] *Natural pen grip changes tools or response of pen*
Hand	• Unimanual Pen+Touch [14] *Switch tools with side vs. heel palm* • PalmTouch [52], • Shape Touch [15] *Action depends on contact shape* • Medusa [2], • Guiard-abiding [81] *Mode differs for left vs. right hand*	**Palm Tools** • Occlusion-Aware Menus [10] *Menu avoids palm occlusion* • Paperweight Metaphor [70] *Rest palm to 'hold down' content* • Palm Rejection [3] *Ignore unintended palm contact*
Arm	• Forearm Menu [1] *User's forearm defines area for menu operation* • SleeD Sleeve Display [90] *Arm-mounted controls for large display input*	**Fan Tools** (Sensed Reach Direction) • Three's Company [73] *Hand shadows for tele-present users* • Medusa [2] *Just-in-Time Widgets as user reaches* • Posture-Based Tabletop Widgets [58] *Forearm ignored during hand contact*
Body	• VIDEOPLACE [48, 49] *Interact via body silhouette* • Lean and Zoom [34] *Magnify screen when lean forward*	**Body-Centric Auto-rotation via Grip + Orientation** • Public Ambient Displays [77] *Respond as users approach* • Medusa [2] *User position tracking around a tabletop* • iRotateGrasp [18] *Grip determines screen orientation*

Table 1. Foreground and Background techniques for multiple Frames-of-reference. Our examples (bold) primarily populate the background, and integrate numerous frames-of-reference.

"gracefully degrade") interactive behaviors and UI controls to the shifting grips and postures that typify tablet interaction. While "mobile vs. stationary use" has been articulated as a key design consideration to allow for graceful degradation of pen+touch interactions to a variety of usage contexts [38], our work (and efforts such as BiTouch and BiPad [80]) show this is not a simple dichotomy. There are many forms and degrees of "mobility" with tablets. Effective adaptation requires sensing and accommodating a diversity of grips, postures, and transitory states of both hands.

Elements of this perspective can be found in a few previous efforts. For example, Sun et al. consider stylus grip as well as screen orientation [71], but the tablet they used was tethered and too large for truly mobile use. An exploration of sensing techniques for stylus+touch interaction [40] included tablet grip sensing, but made little use of the tablet posture and did not include above-screen hand sensing. Our exploration of Posture Awareness integrates many contexts of use (and the transitions between them) to an extent not previously demonstrated for mobile pen+touch interaction.

Since pen+touch affords bimanual interaction—even if one hand primarily supports the device—knowing which hand touches the screen is important. Wearables can sense which hand touches [45, 81], but this approach imposes some latency (since one must delay response to touch until coincident motion can be detected) and requires sensing capabilities extrinsic to the tablet itself. Our approach using bezel-integrated electric field sensing can sense one hand via grip detection and the other via its above-screen approach, before it even touches down on the display.

2.5 Summary

Table 1 illustrates all these reference frames, from exocentric World and Device, to egocentric Grip, Hand, Arm, and Body. This shows how our efforts go beyond previous work by integrating multiple postural elements via sensing. We implement a working system, with practical sensors, and interaction techniques that put these concepts into action. The particular set of sensors we employ (raw capacitance image + inertial motion + electric field) is a sub-contribution that shows how to realize Posture Awareness in a pragmatic way. We believe this articulation and emphasis of posture awareness opens up new possibilities for both stationary and mobile pen+touch interaction on tablets.

3 REALIZING POSTURE-AWARE SENSING

Our system required several software components as well as new hardware. We built our posture-sensing tablet using the detached 12.3-inch screen of a Microsoft Surface Book. This is slightly larger than consumer tablets (iPads), but we needed a device that supported simultaneous pen + touch—as well as access to raw touch data. The Surface Book inertial sensing includes tilt via 3-axis accelerometer.

We modified the touchscreen firmware to stream raw images to our software at 100 Hz. This lets us bypass system touch processing and palm rejection, which otherwise scuttles events for large "palm" contact areas before reaching applications. We threshold low capacitance values to reduce noise and then use standard blob tracking in combination with template matching to detect the position and orientation of the palm or objects placed on the screen.

3.1 Peripheral Electric Field Sensor

For grip and proximal hand detection, we built an electrode ring in the form of a thin overlay on the screen bezel (Fig. 2). This ring consists of 52 individual electrodes that project an electric field around the device, enabling non-contact hand detection within a range of about 5 cm.

3.1.1 Electrodes and Sensor Circuit

The electrode ring consists of a 308×216×0.4 mm flexible printed circuit board with 8×16 mm copper electrodes, evenly spaced at 3.5 mm gaps, with 15 electrodes per long edge and 11 per short edge. Black electrical tape protects the electrodes, which connect to a small circuit board through four FCC cables, amenable to tight integration. A Photon P0 System-on-Chip (SoC) drives the circuit, with four Analog Devices' AD7147 capacitance sensors connected to 13 electrodes each, and the sensor ground connected to the tablet ground. The SoC polls capacitance from each sensor at 10 Hz, and streams the data to the Surface Book through Wi-Fi. The circuit board mounts to the back-center of the tablet, along with a thin 500 mAh lithium-polymer battery, so it does not materially affect device mobility. Four small rubber feet keep the tablet flat.

3.1.2 Signal Processing

Both touch and proximity impart capacitance. But touch increases capacitance by roughly an order of magnitude more than non-contact proximity. We calibrate the sensors by capturing a capacitance baseline for three seconds while no hand is present within a 10 cm range to the tablet. In different electrical environments, re-calibration may be necessary for good signal detection, a practical complexity that we currently sidestep via manual re-calibration as necessary. We then subtract subsequent capacitance measurements from the baseline. We can readily detect grip (touch) events by thresholding. Otherwise, if no touch is detected on an electrode, we use the subtracted results for a z-score computation for hand proximity sensing. If the user touches an electrode, it cannot simultaneously sense proximity because the capacitance of hand contact overwhelms the much weaker above-screen signal.

3.1.3 Sensing Hand Hover & Reach Direction

When the user touches the screen, we estimate the forearm approach angle by searching for a hovering hand at the peak of the electrode z-score sums within a sliding window of 5 capacitance samples, while omitting any electrodes that the user is already touching. We set a threshold on the detected peak value, as well as a majority voter of length=5 on the result to avoid chatter. We calculate the orientation of any detected hand(s) by computing the vector between the touch point and the position of the peak electrode, which we assume must represent the user's forearm.

4 INTERACTION TECHNIQUES

To demonstrate how posture awareness can manifest in pen+touch on tablets, we iteratively designed a series of test applications to explore design issues and challenges that arise. Each includes basic mark-up functionality, allows the user to change pen colors and thicknesses, and at times to invoke a few other commands such as lasso selection mode, copy-paste, and undo. Although minimal, we found these sufficient for users to experience our Tools and sensing techniques—in the spirit of insights gained through 'toy' applications such as GEDIT [50] in the past—and to try representative tasks that elicit the key design challenges of Round Trips, Divided Attention, Comfort, and Occlusion.

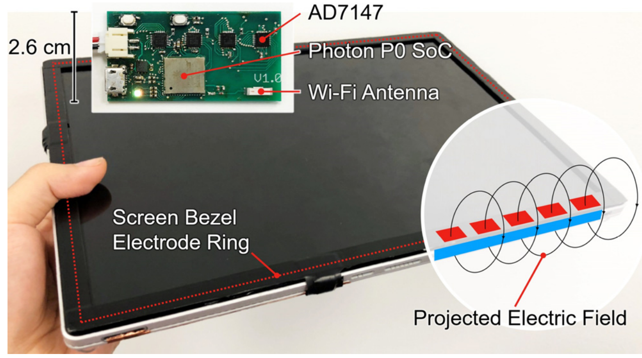

Figure 2. Sensor board mounts on back. Screen bezel projects electric field around tablet. *Circular inset:* Red pads indicate electrodes; blue, shared sensor / device ground.

We do not necessarily seek to optimize time-motion efficiency. Keeping tools close-at-hand may offer benefits [56, 80], but it depends on the task sequence [4, 55]. Unlike desktop productivity, tablets afford casual & informal interaction [16, 39, 44, 65] that rewards convenience, comfort, maintaining attention on one's content, and interacting from a variety of physically relaxed postures. For mobility, such concerns tend to trump minor gains in efficiency. Hence our goal is to make context-appropriate tools available and reachable from a variety of fine-grained postures—to address pen+touch for mobile vs. stationary use [38], unimanual or bimanual, with fingers or thumb, pen or touch (or both simultaneously), and whether a particular sub-task is articulated via the preferred or non-preferred hand—with satisfactory answers often contingent on posture.

4.1 Thumb Tools: Grip-Centric Frame of Reference

When the non-preferred hand grips a tablet, the thumb often remains available for touch [26, 80], lending itself well to mode switching [72] and thumb+pen interaction [63].

Our Posture-Aware Interface senses the presence of the gripping hand and combines this with other information and postural transitions. For example, when the user picks up the tablet with the non-preferred hand, the user interface's linear toolbar scoots over to a position near the hand grip, and morphs into an arc that suits the range-of-motion of the thumb (Fig. 3a & Fig. 4aef). The size of the individual elements also expands to better accommodate the imprecision of thumb input. Thus the layout, radial extent, and

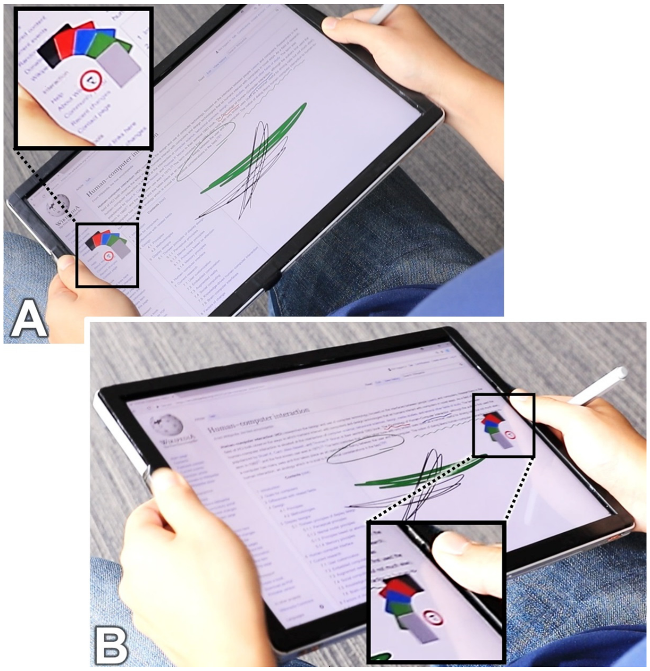

Figure 3. In bimanual grips, using either thumb is plausible. So the user can just physically tip the tablet to slide the Tools to the left or right, resolving the ambiguity.

scale of the Thumb Tools are all tailored to a grip-centric frame of reference.

The Thumb Tools raise a design challenge for posture-aware techniques, that of *contextual responsiveness* vs. *stability*. If the Posture-Aware Interface is over-eager, the tools can very easily ping-pong between different screen locations. In early implementations that did not handle this trade-off well, we found such behavior annoying. But if the UI fails to respond promptly to a change in context, it feels ‘wrong’, the tools remain out of reach, and one wonders why they failed to follow. This suggest the existence of a cost-benefit tradeoff for automatic adaptation to posture.

We addressed this in part through the sensor design. For the purposes of grip sensing, we treat the sensor electrodes as discrete pads (without linear interpolation in-between). Since these pads are spaced at 2 cm intervals, this design naturally keeps small positional shifts from jittering the placement of the Thumb Tools. Yet if the user slides their thumb to a new position for comfort, the Thumb Tools quickly snap to the new grip-centric location.

We also use the sensed grip and the tilt sensor synergistically to decide when to move or dismiss the Thumb Tools. For example, if the user puts down the tablet—such that no grip is sensed—and if the root mean square (RMS) of the three accelerometer axes (over a one-second rolling buffer) falls below a threshold, this indicates the device is stationary. The interface then decides it is safe to revert to a linear toolbar, and does so with an animated transition. But if the device is still in motion during a momentary loss of grip sensing, we assume the user is most likely shifting between transient grips, so we keep the Thumb Tools in a stable location for the time being. Together, these considerations make the tools feel stable while still being responsive to posture changes. And using the electric field sensor, The Thumb Tools fade (20% opacity) as the thumb lifts from the bezel. This lets users see content that happens to fall behind the tools, without having to shift to a new grip location.

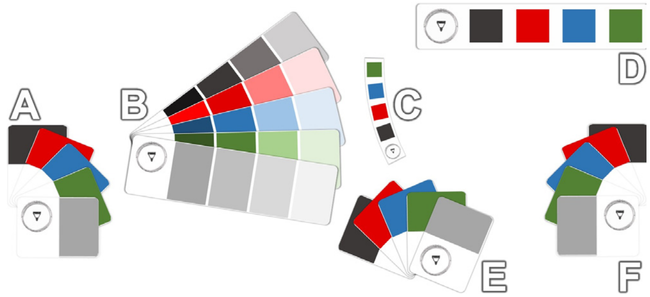

Figure 4. Details of: (A) Left-handed Thumb Tools. (B) Fan Tools splayed to right. (C) The miniature Palm Tools. (D) When the user sets the tablet flat, Default Tools appear near the top-right corner. (E) Bottom-edge Thumb Tools. (F) Right-handed Thumb Tools. In (A-F), the circular icon is an 8-way marking menu with more options.

4.1.1 Tipping the Tablet to Resolve Ambiguous Grips

If the user holds the tablet with both hands, in a two-thumb grip, it is unclear which hand the Tools should flock to. We considered duplicate Tools, with one set for each thumb, but this feels cluttered. Splitting the tools between two thumbs likewise invites constant indecision—which side to use?

To resolve this, we introduced an embodied gesture [22] (Fig. 3). At first, when user naturally holds the tablet with its left-right tilt nearly level, the system shows a faint linear toolbar near the center of the screen to provide visual feedback of this ambiguous state. Then, tilting the tablet by more than 20° morphs the toolbar, with a quick animation, into the Thumb Controls on the corresponding side. We found this to be an intuitive and easily guessable interaction. And once the user “tips” the interface to one hand or the other, it stays there for the duration of the bimanual grip. However, the user can choose to “tip it back again” at any time by angling the tablet by more than twenty degrees in the opposite direction.

4.2 Default Tools: Tablet Flat for Stationary Use

In some usage contexts, such as when the user puts the device down flat, a device-centric placement of UI controls remains appropriate. Once freed from the constraints of supporting the device, both hands can comfortably reach anywhere on the tablet’s screen. We therefore sense when the user sets the tablet down flat and relinquishes their grip. The Tools morph back into a linear toolbar near the top-right of the screen (the "Default Tools"). This provides the user with a familiar resting state that helps show our varied and perhaps unfamiliar Tool sets relate to traditional desktop tool palettes. And since both hands are unencumbered, we also favor behaviors that afford bimanual interaction when the device is flat, whether or not the Default Tools are up, as we will see in some of the following sections.

4.3 Palm Tools: Hand-Centric Frame of Reference

The Thumb Tools discussed above consider grip-centric frames of reference, primarily for the nonpreferred hand, that follow the outer boundaries of the screen. But what about the hand holding the pen, especially when it is involved in sketching, lettering, or heavy line-work? During such tasks, the artist may use a specific hand position and orientation to produce pen strokes with a particular curvature—or to cross-hatch in a well-practiced and precise pattern. In such cases, having to move the hand away to pick a different stroke thickness, or pen color, physically disrupts the work and makes it difficult to continue drawing from the same biomechanical pivot-point where they left off.

To address this problem, we explored location-independent Palm Tools (Fig. 4c & Fig. 5ab) that teleport (with a short animated transition) to a hand-centric location when the user plants their palm on the screen while writing or drawing. This therefore introduces a frame of reference to our Posture-Aware Interface that is preferred-hand-centric. Related techniques such as Tracking Menus [23], Trailing Widgets [25], and Hover Widgets [29] use pen hover sensing as a way to support location-independence [64]. But the very limited range of pen hover (typically 20 mm or less [3]) makes it unreliable as a proxy for the current hand location.

4.3.1 Palm Detection vs. Palm Rejection

We use the raw capacitance image from the touchscreen to detect the palm and place our Palm Tools at a convenient spot nearby. Unlike Occlusion-Aware Menus [10], our technique senses the palm's orientation in addition to the presence of the palm from the raw capacitance image, allowing our system to position controls in a stable and predictable spot even before the pen tip enters hover range. This strategy of *palm detection* stands in sharp contrast to the 'palm rejection' [3] commonplace on tablets today, and shows the value in passing hand contact events on to applications rather than 'rejecting' them (at the firmware or operating system level) outright. It also illustrates how touch can be used as an implicit sensing modality [42], rather than solely as a channel for explicit 'foreground' commands [[14], [58]].

4.3.2 Recognizing Palms

We primed template-matching using a few captures of the palm at varying orientations. High-fidelity palm detection (or rejection) is not an objective of this work. We gathered

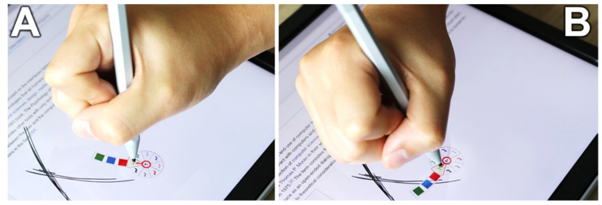

Figure 5. The Palm Tools rotate to match the "up" direction in the hand-centric reference frame of the sensed palm.

about a dozen sample templates per user prior to pilot studies and our informal evaluation, which was sufficient for users to experience our techniques as intended.

4.3.3 Size and Reachability

When the Palm Tools appear, they morph into a curved layout (Fig. 4c) well-suited to the biomechanics of pen movement. The small size keeps all Tools within reach. In a Fitts'-Law sense pointing to small targets has a higher index of difficulty, but they work well since the user can reach the targets with fine motor control from a tripod (precision) pen grip, even while the palm remains planted on the screen.

4.3.4 Relative Orientation and Stability

When the user first plants their palm, the Palm Tools tuck themselves into place 30° counter-clockwise relative to the sensed palm direction to help keep them convenient, but out of the way. The Palm Tools maintain *approximately* the same position relative to the hand, even as the user's palm comes down in different areas of the screen or at different arm angles. In particular, the local "North" of the Palm Tools follows the reference frame of the hand (Fig. 5). Hence, the user can trigger a radial menu command with confidence, knowing that "up" is always hand-centric—even if they are writing in a mobile posture that might require an unusual approach angle.

We also found that keeping the Palm Tools in a stable location was important. Our initial implementation tracked continuously with the sensed palm position and orientation, or as the user glided their palm to a new spot, but this made the tools feel somewhat unstable, and less predictable. And indeed, pilot users found this hyper-sensitivity of the tools annoying. In response, we updated the design to only update the position of the tools when the hand position changed by more than about 1 cm, or the hand orientation changed by more than 45°, but further pilot users still found this could trigger distracting palette movements. We also experimented with a design alternative that only teleports the Palm Tools to the hand when the user explicitly summons them via touching down the thumb of the non-preferred hand. We found this works well, but it precludes using the Palm Tools as a one-handed interaction technique. Furthermore, it puts the burden for managing tools onto the user, which was counter to our design goal of sensing posture and shifting the burden to the computer.

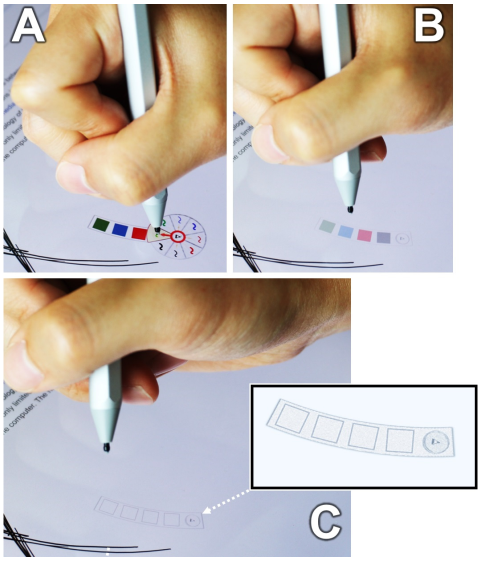

Figure 6. The miniature Palm Tools (A) fade on pen hover (B), and dim to an outline when the palm rolls back (C).

These explorations led us to our final design, which only repositions the Tools when first sensing a palm-down event. This corresponds naturally with user-initiated changes of posture, and makes the tools feel stable and predictable. We found that pilot users strongly preferred this. However, this does mean the Palm Tools placement is not absolutely identical every time the palm touches down, as can be observed in our video figure, due to limitations in how well we can match the initially observed palm contact area to the final resting spot of the palm.

4.3.5 Fade on Roll-Back of the Palm to Reduce Obscuration

During pilot studies we found that reducing the potential overlap of the Palm Menu with content was important, which led us to shrink the Palm Tools to just 40% the scale of the Default Tools. We also made the Palm Tools semi-transparent (Fig. 6b) to reduce any obscuration of content, except when the pen hovers over them (Fig. 6a).

To further limit obscuration, we experimented with sensing partial palm contact. We noticed that artists sometimes pause to inspect their work while sketching: they tip the pen by rolling back the palm, while remaining in contact with the drawing surface. Then, when ready to proceed, they simply re-orient the wrist to return their writing instrument to the same position, orientation, and biomechanical advantage as before.

We therefore sense this change in the raw touchscreen capacitance image of the palm and use it to fade back the Palm Tools to a barely perceptible dim gray outline (Fig. 6c) that minimally obstructs the content on the screen—while also making reappearance of the tools at this location completely predictable for the user.

We define palm roll-back as a decrease in the palm footprint of 15% or more. Even though the centroid of the palm contact region changes during this transition, we keep the Palm Tools in the same stable location. This makes it possible for the user to target the tools with confidence, and with a ballistic motion of the pen, if for example they want to change the color or stroke thickness during line-work.

4.4 Fan Tools: Hand, Grip, and Arm-Centric

To explore the posture-awareness of larger tool palettes with richer sets of tools—analogous to Toolglass and Magic Lenses (TGML) [8] or the Zoom-Catcher of Xia et al. [86], both of which emphasize tool placement by the non-preferred hand—we implemented a set of *Fan Tools*. These also demonstrate the integration of aspects from the Hand, Grip, and Arm reference frames across both hands.

The Fan Tools (see Fig. 4b for detail) take their design inspiration from color sample fan decks, such as those seen in paint stores, which can be splayed out to show a range of hues. Our Fan Tools appear in place (Fig. 7a) when the user touches the screen with two fingers. But a touch-screen cannot sense which hand touches, so a design quandary arises: should the tools splay to the right, or the left?

For example, Xia et al.'s Zoom-Catcher *assumes* that the user touches with two fingers of the left (non-preferred) hand, so its cone-shaped selection tool sweeps out to the right. Webb et al. [81] encounter a similar design issue, and use a wrist-mounted fitness tracker in combination with a large display to sense nonpreferred-hand touches. But this does not address varying posture of use.

Using the above-screen hand detection of our electric field sensor, the Fan Tools can directly sense which direction the hand reaches onto the screen from. The tools then splay out in the opposite direction, so that they are not occluded by the hand. Further, by combining hand approach detection with grip sensing, we also know which hand is available (or not), and can make reasonable inferences about handedness. For example, if the left hand is gripping the device, and we observe a touch event that reaches onto the screen from a different direction, then the touch must come from the user's right hand. In this way, as the interaction progresses, we can properly invoke behaviors for each hand, whether preferred or non-preferred.

But this gets more interesting as we consider fuller posture-awareness. When the user isn't gripping the device and the tilt sensor tells us that the tablet is on a supporting surface (e.g. on a table, or flat on one's lap), we know that both hands are available for bimanual action. So for a right-handed user, if the left hand touches down with two fingers, the Fan Tools splay out to the right (Fig. 7a), and they act as

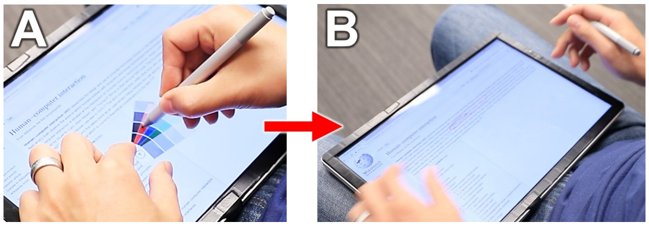

Figure 7. Stationary posture for Fan Tools. With both hands available, the left (non-preferred) invokes tools for simultaneous pen+touch (A); on release, they vanish (B).

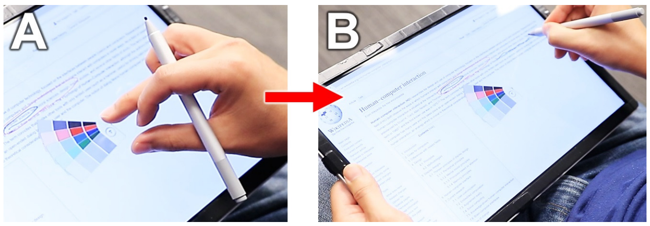

Figure 8. Mobile posture for Fan Tools. The left hand grips the tablet, so only the right (preferred) is available (A); on release, they remain posted for interleaved pen+touch (B).

a quasimode [66] that requires holding the tools in place (i.e. a mode maintained through muscular tension [69]). The preferred hand can then use the pen to pick the desired tool via *simultaneous* pen and touch. In our prototype, letting go from this state (by removing both fingers from the screen) automatically dismisses the Fan Tools (Fig. 7b).

But if the left (non-preferred) hand is instead gripping the tablet to support it, we have a different situation. Here, only the right hand is free to reach onto the screen. A two-finger touch still invokes the Fan Tools, but now they splay out to the left (Fig. 8a). If the user wants to pick a tool with the pen—held of course in the preferred hand—they must let go. So if the Fan Tools automatically dismiss as before (Fig. 7b) they cannot be used from this mobile posture. But by sensing this context, our system knows to instead leave the Fan Tools posted so that the user can instead interact with them with the same hand, via *interleaved* (as opposed to simultaneous) pen and touch (Fig. 8b).

Taken together, these aspects of the Fan Tools show how the combination of grip, tilt, and above-screen hand detection support contextual-adaptation of the technique for each posture. And critically, the burden of maintaining the missing state (i.e. options for how the tools present and behave) is handled entirely in the background by the system.

4.5 Lay Pen Down to Customize

Because the Surface Book pen has a conductive metallic body, we realized that it could be sensed and tracked if the user lays the pen down on the screen. In effect, this allows the pen to act as its own prop. We use this use to bring up a special configuration mode where the user can simply *lay down the pen to customize* (Fig. 9).

One motivation for this technique was to help users discover pen hardware settings that are typically buried deep in system options—and hence rarely noticed or used. By helping users find these settings, they not only learn about their pen—but through the act of customizing and personalizing its operation to make it "theirs," they may come to see it as a more valued possession [7, 62], rather than a generic consumer object of little personal attachment.

When the user lays down the pen, the current application dims (but remains visible in the background) and the system enters a *pen configuration mode*. A phantom of the pen starts tracking its position and orientation, and leader lines appear, to point out hardware control points. These include the pen tip, the barrel button, and the eraser (which is also a customizable button that can be used even when the pen is away from the screen). Excentric radial menus serve as iconic labels at the end of the leader lines (Fig. 1e and Fig. 9c) and allow the user to directly change the default system mapping of the associated hardware element.

For example, the eraser button can be programmed to Undo, Paste, Screen Grab, or Advance Slide functions. The pen's barrel button can trigger various modes such as Lasso, Highlighter, Eraser, or Diagramming mode. And the system default ink style for the pen tip can be set to the user's preferred color and stroke weight. When the user picks up the pen, the system exits pen configuration mode, and the excentric radial menus animate back into to the Default Tools, which helps users see how the settings they just selected connect to application functionality.

4.5.1 Posture Awareness through Imprinting

Self-revelation of hidden functionality by placing the pen on-screen can be taken further through posture awareness. Previous work has explored sensed tangible objects on tablets [5, 53, 89]. But since tablets are used with a variety of mobile postures—where the screen is often tilted, or in constant motion—it's difficult to adopt traditional tangible interactions that rely on a horizontal surface. A slippery screen cannot hold tangibles in place.

To afford mobile postures with our *Lay Pen Down to Customize* technique, we developed the notion of imprinting objects on the screen. Imprinting the pen leaves behind a *phantom* that acts as a proxy for the object. This phantom stays on the screen after the user lifts the pen (Fig. 9c). This also means that lifting the pen from the screen does *not* exit the configuration mode when the tablet is in a mobile posture. Rather, the mode persists—not unlike the way our Fan Tools stayed posted to accommodate one-handed use (Fig. 8b)—and the user instead swipes up to exit the pen configuration mode. This simple adaptation allows the technique to accommodate mobile postures.

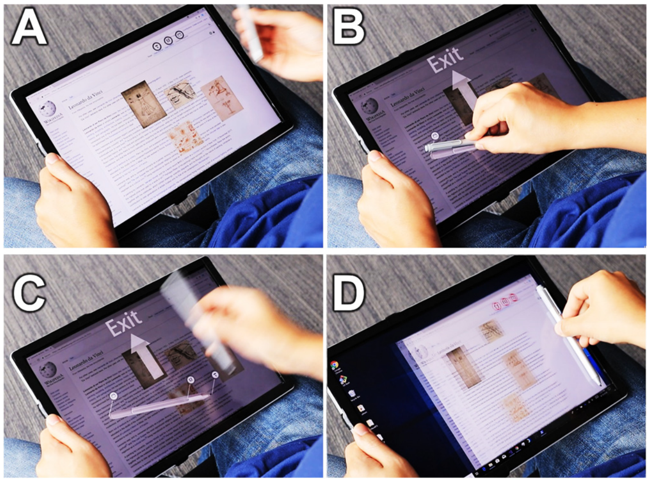

Figure 9. We sense laying down the pen (A→B) to reveal pen hardware settings. During mobile use, this leaves an 'imprint' of the pen on-screen (C). Laying the pen at screen edges allows it to 'pick up' pictures or the current app (D).

4.6 Body-Centric Auto-rotation: Grip + Orientation

Our last example extends Cheng et al.'s iRotateGrasp [18], which uses grip sensing to prevent accidental screen auto-rotation on a mobile phone, to tablets. The technique avoids accidental screen rotation if the user lays on a bed or couch. Cheng et al. use two different grip gestures to determine portrait vs. landscape display orientation.

But our posture-aware interface picks a plausible body-centric reference frame by combining changes in grip with the sensed tablet orientation. If users intend to switch orientation, we observed that this inevitably results in grip changes. However, the grip gesture does not change if the tablet rotates with the user when the user lays down on their side (e.g. on a sofa). Therefore, we built grip-based autorotation, which queries the accelerometer for orientation updates *only when the grip changes*. Specifically, we keep a rolling buffer of the 10 latest gripping states (i.e., roughly 1 second of data). If the buffered grip changes, the tablet looks for a corresponding orientation change for auto-rotation.

5 INFORMAL EVALUATION

We conducted usability assessments with 8 participants. Participants tried the various techniques as they were being developed, and we used their comments and feedback to focus our efforts and make iterative improvements.

5.1 Participants & Procedure

We recruited 8 participants (2 Female) of ages 24-37 (average=28) years. All participants were right-handed, used tablets > 2 years, and had experience with an active stylus. Participants begin by sitting in front of a table with the posture-sensing tablet. But to reflect tablets' real-world usage with different mobility levels, we asked participants to vary their posture for each interaction technique. Specifically, we tested three device postures: (1) gripped in-air, (2) sitting on lap, and (3) flat on table. We also allowed participants to use any variant postures that they found comfortable. For each of the five tested techniques, we showed a demonstration, and then asked participants to try it for 5 minutes, followed by a 10-minute interview. The study took about an hour, with a $15 cafe coupon as gratuity.

5.2 Results

All participants were able to learn the techniques within a few attempts. Overall, our techniques received positive feedback from participants, but we did observe several unanticipated behaviors:

Thumb Tools. 7 participants found it useful to have the tools within the reach of the thumb. One participant mentioned that the animated transition between the default position (i.e., top right corner) and the thumb position was important for understanding what was going on. Once participants discovered thumb grasp tracking, they changed their gripping position multiple times during the usage, most of which were to adjust screen angles. Interestingly, we also found some participants intentionally repositioned their gripping hand to move around the Thumb Tools. In this case, touching the sensing edge was more of a slider than a background sensor as we intended. This hints that users may anticipate and co-opt 'background' sensing techniques as more intentional, foreground gestures when the sensed interaction becomes familiar and expected.

Palm Tools. All participants found this technique useful, making comments such as "The palette is where I need it" and "It's useful in the sense that it minimizes the hand and the pen movement." Others commented from the perspective of focus: "It helps maintain the previous status—both hand posture, and attention" and "It is useful to stay focused on the task such as drawing and writing." However, one participant thought the solidified Palm Tools sometimes got in the way of the area where they wanted to draw, suggesting further use of transparency (e.g. by extending our Fade on Roll-Back feature), or perhaps via positioning logic aware of the underlying content.

Fan Tools. Participants brought up the Fan Tools at many spots, to keep close to the Workspace. One participant said, "It allows me to keep the previous focus/attention by calling fan palette to that location." Another mentioned that he liked to place the palette where needed. Most participants liked the hand awareness, e.g., "It's especially useful for mobile platforms such as phones and pads where I tend to switch hands a lot." Two participants liked that the fan palette knows which way to splay out; two more noted the "smartness" of when it stayed on-screen. However, sometimes participants interacted unimanually, even when both hands were available. This suggests a refinement based on both handedness and hand availability; a palette triggered by the preferred hand should stay posted whenever the non-preferred hand isn't recruited to the task.

Lay Pen Down to Customize. 7 participants found this interaction intuitive. One said that once he discovered this type of interaction, he would want to try it in other applications as well. Two participants liked it as a very explicit way of switching between the configuration mode and the normal inking mode, and the UI was "visually easy to understand." One participant mentioned that "It's hard to have the pen on screen if I'm holding it in the air. It's helpful to have the 'phantom pen' to make interactions more stable."

Body-Centric Auto-rotation via Grip + Orientation. All participants found this helpful; one mentioned "I turn off auto-rotation at night since I don't want the screen rotates when I'm lying in bed. This solves the problem." We observed that all participants shifted grips when they intentionally rotated the screen. However, we also noticed that when they laid on their side, they sometimes lifted off one edge (i.e., from a bimanual thumb grip to a thumb on the right side only), causing false positives. To address this, we could group ergonomically similar gestures into meta-grip gestures and update the autorotation based on higher-level changes to grip, rather than the details of finger placement.

6 DISCUSSION

Our work shows that Posture Aware Interfaces have potential, but this must be tempered by the need for deeper analyses of the trade-offs of sensing techniques. In particular, automatic adaptation of UIs presents a challenge, because UI layout changes could have drawbacks as well as benefits. This arises, for example, with our Thumb Tools: we noted it can be unclear how to adapt when the user grips both sides at the same time. We therefore devised a tipping motion to take advantage of users' natural propensity to tilt the screen in one direction or another to resolve the ambiguity. Our Palm Tools also demonstrate this issue. As noted earlier, following every minor adjustment of the palm annoyed users. But by stabilizing the response (i.e., re-positioning the tools only on initial contact), the technique was well-received.

Clearly, there is a cost-benefit tradeoff of adaptation that one must weigh in the design of such techniques. This challenge deserves more emphasis in future work; over-eager adaptation becomes annoying or unwelcome if this tradeoff is out of balance. Arguably, even techniques in common use—such as automatic screen rotation—are close to the tipping point of this balance: when triggered by accident they can be annoying, and force users to manually turn off autorotation. Yet if users are forced to explicitly change screen orientation, this 'extra step' becomes irksome (or simply gets skipped) during mobile interaction [18, 37].

Missing details of context—as well as discrepancies in the sensed frames-of-reference—both contribute to the problem. For example, the addition of grip-sensing [18] partially solves this challenge for automatic screen orientation, and indeed, our Grip-Based Autorotation technique shows how to refine this further still. Our technique combines *grip-centric* and *world-centric* (device orientation relative to gravity) context to reason about the correct and desired experience in a *body-centric* frame of reference. Building sensors and techniques that can reliably bridge these (and other) natural reference frames remains a challenge.

Unusual postures, such as those that users might temporarily employ during situational impairments, pose another challenge. Our techniques recognize certain grip-states, and take continuous changes into account. But users might still hold their devices in other, unanticipated ways that would confuse our techniques. Designing for fail-safe states—such as the standard placement of our Default Tools when the device is flat—might be one reasonable way to handle uncertain inputs. But at present our system does not attempt to recognize such states; larger data sets from longitudinal, real-world use would also be helpful in this regard.

Finally, while our techniques demonstrate postural awareness, formal experiments must quantitatively assess various trade-offs of time, attention, biomechanical comfort, and learnability. During mobile use, comfort (for example) may be more important to users than time-motion efficiency, but during other tasks attention could be paramount. These factors need to be studied so that we can understand what to optimize for, when, depending on task and context (e.g. [4, 55]). It would also be interesting to study usage patterns as users learn to anticipate sensor responses.

7 CONCLUSION

Overall, our work demonstrates how posture awareness can adapt interaction, and morph user interface elements, to suit the fine-grained context of use for pen and touch interaction on tablets. Posture-awareness includes nuances of grip, the angle of the tablet, the presence and orientation of the palm on the screen while writing or sketching, and which direction the user reaches onto the screen from during touch. Taken together, these contributions show how a few simple sensors can enable tablets to more effectively support both 'mobile' and 'stationary' use—and the many gradations in-between.

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