Cito: An Actuated Smartwatch for Extended Interactions

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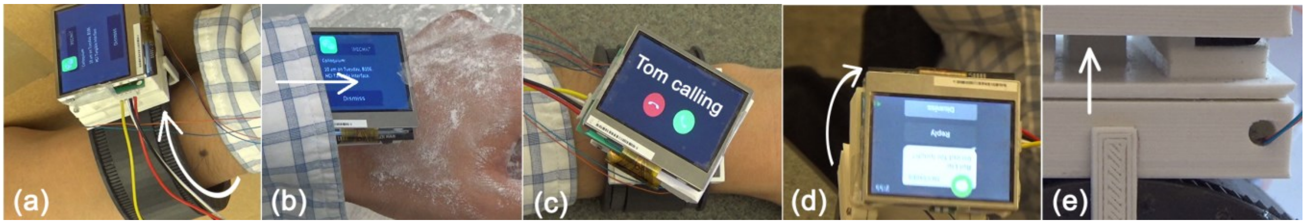

Figure 1. Actuated face movements and usage scenarios: (a) face orbiting for view adaption; (b) face translating outside sleeve; (c) face rotating to indicate an important call; (d) face tilting for sharing; (e) face rising for force feedback.

ABSTRACT
We propose and explore actuating a smartwatch face to enable extended interactions. Five face movements are defined: rotation, hinging, translation, rising, and orbiting. These movements are incorporated into interaction techniques to address limitations of a fixed watch face. A 20-person study uses concept videos of a passive low fidelity prototype to confirm the usefulness of the actuated interaction techniques. A second 20-person study uses 3D rendered animations to access social acceptability and perceived comfort for different actuation dynamics and usage contexts. Finally, we present Cito, a high-fidelity proof-of-concept hardware prototype that investigates technical challenges.

Author Keywords
Actuated UI; Smartwatch; Interaction Techniques

ACM Classification Keywords
H.5.2. Information Interfaces (e.g., HCI): Input devices.

INTRODUCTION
Exploiting the full potential of smartwatches requires useful and usable input and output. This is challenging considering the small form factor and wearable context. Existing research has primarily focused on smartwatch input [7, 12, 14, 16, 19, 21, 29, 37, 46, 57, 65, 72] with little work on output. Smartwatch output has mainly focused on extending the display region such as projecting visual content onto the forearm [45], adding a miniature secondary display on the watch band [4], adding a second watch face [63], or converting the entire watch band into a touchscreen [38]. Haptic output has also been explored, and was found effective in many usage scenarios. Examples include vibrating [34] or dragging a physical tactor across the skin [27] to deliver non-visual messages.

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We propose extending smartwatch output by physically actuating a watch face in five ways: rotating on its normal axis, hinging on side, rising vertically, translating along the forearm, and orbiting around the wristband (Figure 1). These movements can be used for a variety of new interactions. For example, when a user has dirty hands (e.g. gardening), the watch face can *translate* outside of a shirt sleeve to make it visible when a notification arrives. When a user is carrying something heavy, the watch face can *orbit* to a visible part of the watch band. When a user shows a picture on their watch to someone else, the face can *hinge* towards the other person to provide a better viewing angle. If a user needs to receive GPS navigation instructions while they do something else on the watch, the face can physically *rotate* to indicate when to turn a corner. Finally, the watch could *rise* when the phone rings, enabling the user to decline the call eyes-free by pressing the face down like a haptic force-feedback button.

Our focus is on the Human-Computer Interaction aspect of an actuated watch, we iteratively evaluated prototypes of different fidelities presented in different formats. In our first study, we elicit user feedback from 20 participants about actuated watch movements in seven usage scenarios via conceptual videos using a passive prototype. The result confirmed the usefulness of an actuated smartwatch for addressing limitations of a fixed watch face. To further advance our understanding, we conducted another 20-participant study to investigate the social acceptability and comfort of various actuation dynamics when performed in front of different audiences. Forty actuations were presented using 3D animations. The results suggest kinds of movements that should be avoided in certain situations. Finally, we present a high-fidelity hardware prototype called Cito. The device is composed of a miniature LCD display and a modular mechanical system supporting all five actuated movements using electronic actuators (gear motors) with controlling circuits. This paper investigates technical challenges and demonstrates interaction techniques in way that is closer to a real device.

Our primary contributions are: 1) the concept of an actuated smartwatch with five kinds of movements; 2) a set of interaction techniques that address limitations of a fixed watch face; 3) the results of a user study with a passive prototype that validates the usefulness of the concept; 4) the results of a user study using 3D animations and a passive prototype that evaluates acceptability and comfort of different parameters of actuation; 5) the design and implementation of a working proof-of-concept high fidelity prototype.

RELATED WORK

We review related research in novel smartwatch interaction techniques, self-actuated mobile, and wrist wearable devices.

Smartwatch Input

For the most part, research on input techniques has been focused on methods that can go beyond touchscreen input. Existing techniques include using the bezel [8], outside of the watch case [44], or the watch band [54] as an interactive touch surface. It is also possible to physically rotate the watch frame [50], twist, tilt, or push the watch face like a joystick to trigger different actions [68]. An external device (e.g. a smartphone) can also be used to enable joint-device interactions [13]. Doppio [63] introduces a second touchscreen that can be used as a tangible input device. Another major approach explores using the space near the smartwatch for input. For example, Skin buttons [32] has touch sensitive buttons on the skin near the watch. SkinTrack [73] senses continuous finger movement on the forearm. Abracadabra [22] senses the finger movement in the mid-air around the watch. Gesture Watch [30] uses proximity sensors to detect mid-air hand gestures. Blasko et al. [9] used a retractable string to interact with the smartwatch. Last but not least, pinch (e.g. thumb touching the other fingers) [1, 7, 16, 23, 37, 46, 61, 72] and hand postures (e.g. fist or thumb-up) [16, 19, 57, 72] have been used to interact with the smartwatches using the watch hand.

Smartwatch Output

In contrast, little research has been focused on output. A majority of work in this class has been focused on extending the display of the smartwatches. For example, Lenovo's concept smartwatch [4] has a miniature second display, which can only be viewed by holding it to the eye. Doppio [63] double the size of the display by adding another touchscreen to the watch. The screen of the Ken Xin Da's smartwatch [3] can be slid open to review a hidden keyboard. AugmentedForearm [45] extends the smartwatch display to the entire forearm. Other approaches convert the entire wristband into a touchscreen [11, 38]. Haptics has also been used for output. Aside from the well-studied vibrotactile feedback [34], researchers have proposed to use air flow [33] and dragging the skin [27] to deliver haptic messages. Haptic force feedback can enable rich interactions [64] but it has not been made available on a smartwatch. Our approach provide force feedback via actuating the watch face in a vertical motion, similar to [64]. The physical movements of the screen can also serve as visual output in addition to the screen contents.

Actuated Mobile Devices

Larger actuated user interfaces have been widely studied in tangible UIs [40, 43, 51, 53, 67], novel display techniques [6, 18, 28, 35, 36, 42, 47, 56, 66], and shape changing devices [17, 20, 24-26, 48, 49, 59, 69]. Shape changing and self-actuated smartphones provide useful insights to our research. It has been shown that deforming the body of a smartphone can be used for input [31, 62] or providing dynamic affordances [59]. More relevant to our research is the wide range of previous work in self-actuated smartphones. For example, The Ambient Life project [24] and Shape-Changing Mobiles [25] use device shape change to provide haptic feedback. Dimitriadis and Alexander [17] evaluated the effectiveness of shape change in delivering haptic notifications. Animate Mobiles [26] use shape change to show status change on a smartphone. Gomes, et al. [20] studied how effective visual shape change can be used to deliver various notifications. Vibkinesis [69] change the device orientation to show missing notifications. Finally, emotional expressions can be conveyed more expressively using a shape changing mobile phone [48, 49]. Rovables [15] is a wearable display that crawls on the body but it was not designed in a watch form factor. We show that the aforementioned benefits in output can be brought into a small watch form factor via an actuated watch face, alone with many other unique benefits.

Actuated Wrist Wearables

Our literature search revealed little work in shape changing or self-actuated wrist wearables. SmartSound [2] and Lenovo's flexible smartphone [5] can be manually bent around the wrist to form a wristband. LineFORM [41] and PneUI [70] are self-actuated conceptual devices that can transform into the shape of a wristband but they do not function like a regular smart wristband. More importantly, none of these devices provides the look and feel of a wrist watch. Samsung's patent of a flip screen smartwatch [71] is most relevant to our work. However, the device's display can only hinge open from the south side of the watch. We set apart our research from this conceptual device by exploring five different ways a watch face can be actuated. We also propose a set of new interaction techniques enabled by these movements to facilitate interacting with a smartwatch in different contexts. Finally, we investigated issues associated with social and comfort acceptability of this new concept.

WATCH FACE ACTUATION SPACE

A rectangular watch face can be actuated in many different ways, we focus on rigid body transformation with five one-dimensional linear movements, *Hinging, Translation, Rotation, Rising,* and *Orbiting*. We describe them in detail, then discuss common parameters that can affect the movements.

Hinge. The face tilts open to a certain degree (e.g. 0° to 180°) in a desired direction (e.g. north, east, south, or west side of the watch face). The face stands vertically (e.g. perpendicular to the wrist) or flips outwards up-side-down after hinging 90° and 180° respectively. Samsung's smartwatch patent [71] hinges in one direction, south.

Translation. The face moves parallel to the forearm. For instance, moving the face away from the west side of the watch translates the face to the dorsal of the forearm. Translating the face towards the northwest side of the watch moves the face to somewhere in the mid-air.

Rotation. The face pivots around the normal vector of the watch base. In principle, the rotation axis can be anywhere on the watch face but we focus on the center. The watch face is viewed in a portrait mode after rotating 90°, and rotating the face 180° turns the face up-side-down. Although upside down has the same landscape aspect ratio as the default rest position, this can be clearly distinguished with visual cues. Rotated direction may be clockwise or counter-clockwise.

Rise. The watch face moves in a dimension perpendicular to the screen (or z axis). When rising, the face lifts vertically to a certain height from the wrist. It can also move back to its rest position.

Orbit. The watch face moves around the wrist band in either direction, and eventually returns to its rest position. For example, the screen will be on the ventral side of the wrist midway through a complete orbit.

The five movements can be performed independently or combined. For example, the face can rotate while orbiting around the wrist, or hinge open during translation.

Parameters of Face Actuation

We use three parameters from Roudaut et al.'s actuation resolution for deformable surfaces [59]: amplitude, strength, and speed. We added a new parameter, cycle.

Amplitude defines the distance between the start and end position of a face movement. This can be Euclidean (translation and rise) or angular distance (hinge, rotation, and orbit). For instance, the watch face in its rest position has 0° amplitude, and portrait mode has amplitude of 90° or 270°. The amplitude of a movement depends on applications. For example, if the watch face needs to hinge towards the user's eyes, the amplitude is determined by the angle between the orientation of the watch face and the user's eyes. Amplitude is also limited by physical constrains. For example, the face can only hinge towards the west side of the watch until it collides with the forearm.

Speed defines the time required to move the watch face from its rest position to the destination position. The speed of movement also depends on applications and the context of use. For example, rotating the face to show progress (e.g. a file download percentage) may vary in speed, depending on throughput. Speed is also limited by hardware. For example, DC motors are faster than stepper motors. In general, motors are faster than shape memory alloys.

Strength defines the force needed to move the watch face from the start position to the maximum amplitude. A minimum strength is needed to actuate the mass of the face, but strength can also be used for force feedback. For example, spring stiffness can be displayed haptically via the force required to push the screen down to the rest position from a certain height. The strength is also limited by hardware. For example, large motors capable of generating higher torque can provide higher strength than small ones.

Cycle defines whether a movement is repeated. When performed once, the watch face remains in the maximum amplitude of a movement. When performed repeatedly, the movement reverses after the face reaches the maximum amplitude, and repeats until it is stopped. Reversion is not necessary for orbit and rotate if they end at the rest position.

ACTUATED SMARTWATCH INTERACTION

With this actuation space, we posit three primary capabilities enabled by an actuated watch face.

C1 - View Adaptation: The watch face can change its position and orientation to facilitate users' needs. When the screen is facing an awkward orientation, it can be automatically turned towards user. This is useful when the user's hands are not available.

C2 - Shape Display: The physical movement of the watch face can be used as an auxiliary visual output channel. This can be a useful additional to the small display of smartwatches. The watch face has five degrees-of-freedom (e.g. the five movements), providing richer expressions than the existing auxiliary output on smart devices, such as notification LED.

C3 - Force Feedback: The watch face can provide haptic feedback via various physical movements. This goes beyond the existing vibrotactile feedback on smartwatches and enables many new ways to interact with a smartwatch.

We propose specific usage contexts where these capabilities would be useful to mitigate limitations of fixed faces. We evaluate the usefulness of these capabilities in each of these scenarios in a later section (figures in this section are taken from concept videos used in that evaluation).

Watch Hand Unavailable (mitigated by C1)

In many situations, the display of the smartwatch can face an awkward orientation but the hand wearing the watch (e.g. watch hand) is unavailable to adjust the watch face due to the hand performing a task. Carrying a heavy object is an example (Figure 2b). In other situations, such as cycling, it is possible to temporarily take off the hand from the handlebar but this is not preferred due to safety reasons. With the current practices, the user will need to interrupt the task (e.g. put down the object) to free the watch hand before it can be used to adjust the orientation of the smartwatch. This can be inconvenient for the user.

With an actuated watch face, the screen can move automatically towards the user's eyes when a notification arrives. For example, when the hands are holding a heavy object in front of the body, the watch face can orbit to the ventral side of the wrist to allow the user to simply look down to see the screen (Figure 2c). When the user is cycling, the screen can hinge towards the user's head to make it more visible. The face can also move to a closer location towards the eyes by translating along the forearm. This way the user can quickly look down to read the message without taking the hand off the handlebar. The same technique can be used to hide the watch face from untrusted people to protect privacy.

Figure 2. Watch hand unavailable: (a) Passive low fidelity prototype; (b) Watch faces the ground when the user carries an object; (c) Face orbits to the visible part of the wrist band.

Non-watch Hand Unavailable (mitigated by C1)

In many situations, the display of the watch can be covered by the sleeve but the user does not want to use a dirty hand (non-watch hand) to pull the sleeve to reveal the watch display (e.g. working in a construction site or gardening). In other situations, the user may want to hide the watch under sleeve to protect it from dust but the hands are dirty (Figure 4a). Both situations can be inconvenient for the user because it requires the user to interrupt the current task or the sleeve and the watch may get dirty.

With an actuated watch face, the screen can move automatically outside the sleeve when a notification comes (Figure 4c). This way the user does not need to interrupt the current task to see the notification. Similarly, the screen can move inside the sleeve (Figure 4b) when it receives a gestural command performed by watch hand [21].

Figure 3. Non-watch hand unavailable: (a) Watch face gets dirty when working in a dirty environment; (b) Face hides inside sleeve to avoid dust; (c) Face moves out of sleeve.

Watch Unavailable (mitigated by C2)

In many situations, the smartwatch may become temporarily unavailable to the user (e.g. for several minutes). For example, when the user goes to a shower leaving the smartwatch on a desk, when the user is talking on the phone using the watch hand or when the battery of the smartwatch is dead, the smartwatch may become temporarily unavailable (Figure 4a). When this happens, it is often that the user may forget to immediately check missing notifications when the device becomes available again. As a result, the user may miss important messages. The notification LED on many Android smartphones could be adopted on smartwatches. However, the LED is un-functional when the watch battery is dead.

An actuated smartwatch can remind the user to check it if there is a missing notification by moving the watch face to a non-rest position. The odd appearance can catch the user's attention when the device becomes available again. Different movement can be used to show different watch states (e.g. received a new notification, watch disconnected from the smartphone, etc.). This approach works after the battery is discharged (Figure 4b). It is similar to [69] but works in a smartwatch form factor with many more expressions.

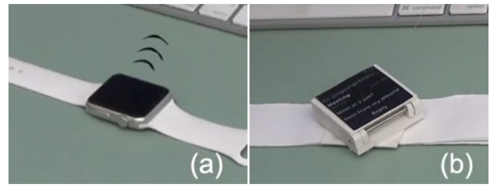

Figure 4. Watch unavailable: (a) Messages come when the user is away; (b) Face in an odd orientation as a reminder

User Unavailable (mitigated by C2)

In some cases, the user may only be able to divert their visual attention from their current task for a short period (e.g. playing a video game or using a rotary tool) but reading the screen content may require a longer duration. However, smartwatch notifications composed of text messages may look alike and cannot be distinguished easily without reading the messages. Switching a user's visual attention from the game is undesired as it may result in negative impact, such as losing the game. Similarly, taking the eyes off the rotary tool when working may have bad consequences. Audio and vibrotactile feedback is available in the current smartwatch but audio feedback may not work in these situations as the user may wear a headphone (Figure 5a) or due to noise of the rotary tool. Vibrotactile feedback can also be missed in many situations [10]. Distinguishing different notifications via vibrotactile feedback requires more cognitive overhead, and can be significantly slower and error prone than using visual feedback [55]. Ambient LED displays [39] are constrained to the 2D watch plane thus limited in output expressiveness.

Figure 5. User unavailable: (a) User misses audio notifications when using a headset; (b) Face rotates to indicate an emergency call; (c) Face mimics mouth movement to indicate a lunch appointment.

An actuated smartwatch has five degrees of freedom so that the watch face can move in five different ways or in a combined manner to provide distinguishable visual feedback to indicate different types notifications. Within each of the five movements, speed and amplitude can also be adjusted to provide even more different movements. The visual feedback can be expressive through the physical movement of the watch face. For example, hinging the screen open and close repeatedly can mimic an animated mouth, which can be used to indicate an upcoming lunch appointment (Figure 5c). Rotating the screen fast can indicate an emergency call (Figure 5b). These can be seen using glance even the display of the smartwatch is not directly facing the user's eyes. Tapping the touchscreen stops the animation and transitions the face back to the rest position.

Screen Space Unavailable (mitigated by C2, C3)

An actuated smartwatch can also help mitigate issues introduced by the small touchscreen. For example, multi-tasking is cumbersome on a smartwatch. Consider using a map app to navigate in a new environment while simultaneously reading or texting a message. This is difficult because the user must frequently switch between the messaging and map apps. Actuation is an alternative approach to using ambient LED displays [39]. Actuation also provides haptic feedback useful for eyes-free use.

With an actuated smartwatch, the face orientation can be used to physically indicate the direction to walk. For example, the face can rotate to point at the right direction for the user to follow (Figure 6b). The virtual canvas can rotate in an opposite direction to allow digital content to remain oriented towards the user. The navigation works even when the user's eyes are temporarily off the screen as the user can use the other hand to feel the screen orientation. This way the message app can remain in the foreground and the two apps can run simultaneously, avoiding switching between them. When the user arrived in the destination, the user can show a photo to a colleague with the watch face hinges towards the colleague. This way the user does not need to stretch the arm towards the colleague's eyes (Figure 6a).

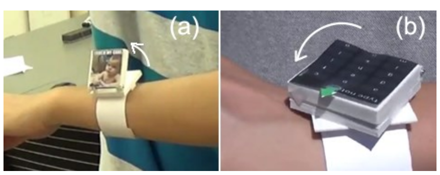

Figure 6. Screen Space Unavailable: (a) Face hinges towards the guest for sharing; (b) Face rotates to show direction.

Haptic Feedback (Introduced by C3)

Haptic feedback can provide rich user experiences in many applications [64]. However, the existing smartwatches can only vibrate thus offering very limited haptic user experience. With an actuated watch face, force feedback can be provided first time on a smartwatch. Using the rising motion we are able to generate a force perpendicular to the touchscreen, similar to TouchMover [64] (Figure 13a). In a simple application allowing people to feel the rigidness of different virtual objects, the user needs to press the screen harder on a rigid object than on a soft one. Another way to provide haptic feedback is flipping the face open to physically 'tap' the back of the user's hand (Figure 13b). This is an alternative way to notify the user about a message.

STUDY 1: USEFULNESS

The goal of the study is to validate the subjective reaction to actuated watch capabilities and their potential usefulness. We took a standard HCI research approach, where the concept usefulness is assessed using a low fidelity prototype.

Participants

Twenty participants (9 female, ages 18 to 30) were recruited. Eight owned or had used a smartwatch previously.

Low Fidelity Prototype

We created a passive prototype approximately the same size as current smartwatches. It was 3D printed with moving parts connected using hinges and tracks to support four of the face movements: hinging, translation, rotation, and orbit (illustrated in Figures 3 to 6). Rise was not included due to implementation complexity. Actuation was accomplished by pulling an attached fishing line, essentially using puppetry to simulate movements. The watch display was a colour paper print. Although somewhat crude, our low-fidelity prototype encouraged participants to focus on usefulness rather than details like hardware fit and finish, or specific interfaces with a high-fidelity prototype.

Protocol

Participants provided ratings and comments after viewing concept videos of actors using the prototype. Concept videos have been used successfully in previous evaluations for futuristic devices such as shape-changing phones [52]. Using videos allowed our study to be highly controlled as participants had to saw the same demos. The videos also encouraged "suspension of disbelief", allowing them to focus on the Cito concept, rather than implementation details. Seven representative scenarios were chosen from the previous section (see Table 1). Haptic feedback was not included since it is a new capability for interaction rather than directly addressing a current limitation. For each scenario, participants watched a short video describing one of the examples from S1 to S7, and respond to the question "I see this is an issue of the current smartwatches" using a 7-point Likert scale. Then they watched another video illustrating how an actuated watch face can be used in the same context, and they responded to the questions stating "this technique is *useful*" and "this technique looks *enjoyable*" also using 7-point Likert scales. We

Scenario	Interaction Technique
S1: User carries a heavy object in front of the body, and watch faces down (Figure 2b).	T1: Face orbits to the other side of the wrist to make it visible (Figure 2c).
S2: Watch face exposed to dust or water (Figure 3a).	T2: Face hides inside sleeve (Figure 3b)
S3: Watch face occluded by sleeve.	T3: Face moves out of sleeve to show a message (Figure 3c).
S4: User plays a video game with a headset when notifications come (Figure 5a).	T4a: Face rotates to indicate an emergency call (Figure 5b). T4b: Face acts like an open/close mouth to show a lunch appointment (Figure 5c)
S5: User forgets to check notifications after shower (Figure 4a).	T5: Face stays at 45°to remind the user to check the missing notifications (Figure 4b).
S6: User multi-tasks by switching between message and map app	T6: User texts on the watch, and face rotates to indicate direction (Figure 6b)
S7: User shares a photo with a friend	T7: Face hinges towards the friend (Figure 6a)

Table 1. Tested scenarios and actuated smartwatch techniques

encouraged participants to think about alternatives and rate Cito low if they saw it as less useful. Scenarios and techniques were kept simple so ideas were conveyed easily. The accompanying video provides examples of the concept videos with the prototype.

Results

Study results were analyzed using Friedman signed-rank tests with Wilcoxon tests used for pair-wise comparisons with Bonferroni corrections. Friedman test yielded a significant difference in Scenarios ($\chi^2(6) = 20.993$, $p < 0.01$) and Technique Usefulness ($\chi^2(7) = 22.59$, $p < 0.01$). There was a borderline significant difference in Technique Enjoyment ($\chi^2(7) = 14.204$, $p = 0.048$).

Overall, median ratings for all scenarios were above 4 indicating all or most participants perceived the issues portrayed in each scenario as a current problem with smartwatches. S3 (sleeve occlusion) and S6 (multi-tasking) had median scores of 7 (with 1 being strongly disagree and 7 being strongly agree). Participant comments indicate sleeve occlusion is frequent, *"I have this problem a lot" (P11),* and frustrating, *"I always get fussed when a message come but I can't take a look at it while cooking" (P4)*. Participants noted a similar issue when *"both my hands are occupied by some small stuffs" (P1)*. For multi-tasking, participants said switching between apps is annoying and challenging, *"It's hard to multitask on such a small screen" (P7)*. S7 (sharing) received a low median score of 5, significantly lower than S3 and S6 ($p < 0.05$). Participant comments indicate they did not think sharing is a problem because content on smartwatches is not typically shared. However, if sharing was common, they agreed it was difficult with current smartwatches, *"not a problem I generally have but can see how it would be" (P11)*.

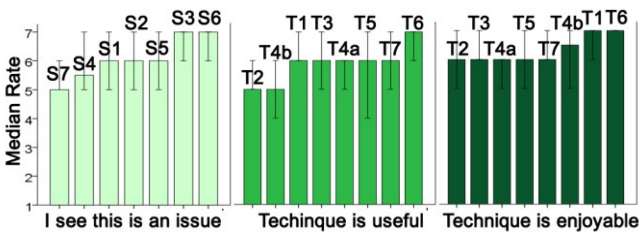

Figure 7. Median ratings for: scenario usefulness; technique usefulness; and technique enjoyment. Error bars show 95% confidence intervals.

Median ratings for technique usefulness were all above 4, indicating all or most participants considered the proposed interaction techniques useful for addressing the issues described in the scenarios. T6 (multi-tasking) had a median score of 7. Participants considered it *"one of the coolest features" (P12)*. T1 (reorienting face), T3 (escaping sleeve), T4a (emergency call), T5 (notification reminder), and T7 (hinge for sharing) all had median scores of 6. Participants liked T1 and considered it *"very handy!" (P7)*. They saw themselves using T3 to solve the sleeve occlusion problem, *" I would definitely use this feature." (P10)*. Showing notifications using shape display (T4a and T4b) was considered cute (P6), nifty (P7), and useful, *"I like playing computer games a lot. I will take advantage of it." (P9)*. Note that T4b (mouth movement) was considered less suitable in public as it *"could be strange and awkward" (P8)*. Participants liked T5, *"it is amazing. I have suffered this many times before, and it should work using the proposed method" (P2)*. T7 was also considered useful, and can be handier than simply tilting the watch face towards a guest. Finally, T2 (hiding inside sleeve) was rated less useful than T6 ($p < 0.05$) (but no significant difference from the others) because it requires the users to wear a sleeve. Participants commented that a water and/or dust proof solution could also be helpful. For all but one scenario, at least half of the eight smartwatch users encountered the situation more than once.

Median ratings for technique enjoyment were all above 5, indicating all or most participants enjoyed the face movements. It is worth mentioning that T6 received a rating of 7 again in addition to usefulness. Overall, the result is promising as enjoyment is an important fact that motivates people to use a technology [58].

Discussion

The result confirms the proposed interaction techniques are useful in mitigating smartwatch issues. Participant comments also suggested aspects for further study.

Social acceptability. An actuated smartwatch will be worn by the users in a variety of different social environments. However, a moving watch face may possibly impose negative impacts to the user. Our study has shown that participants worried about using T4b in public as the movement could be *"disturbing to the others" (P8, P9, P11, P12)*.

Comfort and safety. Wearing comfort may affect the usability of the device as the watch face may hinder normal hand movements in certain situations, such as sporting (P9, P11). Safety is an important concern for many actuated hardware user interfaces as the moving part may potentially harm the user. A participant asked *"is the movement harmful to the skin?" (P11)*. Another participant worried that *"the track might cut myself when exposed" (P12)*.

Meanings of face movements. There was some disagreement between our design and user's expectation of the meanings of different face movements. For example, a participant expect to see *"lift rather than rotate" (P4)* in T5. Another participant thought that instead of feeling like a notification, rotating the face 45° feels *"like it is broken" (P13)*.

Among these, social acceptability is arguably the most important at the current stage of this research. In the next section, we present our study, investigating the social acceptance. We also saw that comfort of face movements could also be briefly assessed using our low-fidelity prototype.

STUDY 2: SOCIAL ACCEPTABILITY AND COMFORT

The goal is to assess social acceptability and perceived comfort for different actuation dynamics and usage contexts.

Participants
Twenty participants (6 female, ages 22 to 30) were recruited. Nine either owned or had used a smartwatch previously.

3D Animations
We illustrated different face actuation dynamics using 3D modelling and animation software. A 3D model of a smartwatch face with texture mapped display and a watch band were placed on and around a 3D model of a human arm. A virtual camera was positioned to mimic the view of a person wearing the watch. Ambient diffuse light provided a clear view of face movements with minimal shadows. Each silent animation lasted 4 to 100 seconds. Figure 8 shows frames taken frames from each of the five movement types.

In the study, participants viewed the animations and answered question. Participants could also try on the low fidelity prototype used in Study 1 and manually actuate the movements like the animations using their hands. This gave some sense for what different actuations felt like. This general method using video prototypes has been also used to identify acceptable or unacceptable interaction techniques [58].

Figure 8. Example animation frames (top row): rotate 45°, translate small, hinge small; (bottom row) rise large, orbit 90°.

Face Movements
Each animation illustrated a face movement type (*rotate*, *orbit*, etc.) with different levels of three actuation parameters: *amplitude*, *cycle,* and *speed*. Animations cannot easily illustrate the strength parameter, so it was not included. The selected levels were informed by pilot evaluations.

Amplitude had two levels: small and large. For *hinge* and *rotation*, we used 45° and 90°. For *orbit*, we used 90° and 180° since the pilot showed 45° orbits were difficult to notice. For translate, the small amplitude was the face width (to move the face to the west side of the watch) and the large amplitude was 4 times the face width (to move the face to the middle of the forearm). For rise, the amplitudes were 1.5 and 5 times the face thickness, similar to [52]. For simplicity, we only tested one movement direction. Cycle had two levels: a single movement or three cyclic repeated movements. Speed had two levels: slow and fast. When the face moved slowly, each small movement completed in 5s and each large movement in 10s. When the face moved fast, the movements finished in 0.3 and 0.6s for small and large amplitudes respectively. These remained the same for all the movements.

All combinations of 2 settings with 3 parameters produce 8 different animations per movement type, 40 animations for all 5 movements. Note the speeds and amplitudes were only used to demonstrate actuation dynamics for the purpose of relative comparison, they do not represent real device speeds.

Protocol
The study was implemented as a web form, but participants completed the study in a lab with the experimenter present. For each type of face movement, the form presented 8 embedded animations illustrating different movement dynamics. Participants were free to view the animations or try the low fidelity prototype as many times as they wished before or while answering questions.

Below each animation was a series of form elements to answer three questions. The first question was about social acceptability. Participants were asked to imagine wearing the actuated watch in the presence of different people representing different social situations. Then, for each animation, the participant answered yes-or-no regarding which audience(s) ("Alone", "Partner", "Family", "Friends", "Colleagues", "Strangers") they would feel comfortable with while wearing a watch that actuated in the way shown in the animation. They also answered yes-or-no indicating whether they would be bothered by an actuated watch face worn by a member of those same audiences (except "Alone"). Finally, participants also rated the perceived comfort when the watch actuated in the way shown in the animation using a 7-point Likert scale.

Results
The two social acceptance yes-or-no responses were analyzed using Cochran's Q test with McNemar's test for pairwise comparisons. Comfort Likert ratings were analyzed using Friedman test with Wilcoxon test used for pair-wise comparisons. Significance levels were adjusted using Bonferroni's correction when multiple tests were taken.

Social Acceptance
For the question "With whom you are willing to use face actuation?" there was a significant difference in Audience ($\chi^2(5) = 1278.68$, $p < 0.001$), Movement ($\chi^2(4) = 262.59$, $p < 0.001$), Speed ($\chi^2(1) = 31.15$, $p < 0.001$), Amplitude ($\chi^2(1) = 270.1$, $p < 0.001$), and Cycle ($\chi^2(1) = 270.56$, $p < 0.001$).

Post-hoc analysis showed significant differences between all pairs of audiences (all $p < 0.001$) except partner and family ($p = 0.46$). Alone was rated the highest (94%). The acceptance rate decreases as the level of familiarity with the audience decreases. More than 60% of participants felt it acceptable to use the actuated watch face in front their partner, family, or friends. However, less than 40% of them are willing to use it in front of colleagues and strangers. There were significant differences between all pairs of movements (all $p < 0.001$) except rise and hinge ($p = 1$). Among the five movements, rotation was rated the most socially accepted, followed by rise, hinge, and orbit. Translation was rated the least socially accepted. This is mainly because the movement is noticeable, especially large amplitude. We observed a similar trend across all audience types (Figure 9). Participants found subtle movements more socially acceptable. In particular, non-repeating, small amplitude movements were significantly more acceptable regardless of movement type.

Our results suggest certain movements to avoid in some social situations. Participants commented that repeated movements involving large amplitudes and high speed would be distracting to others. P9 commented repeated high-speed raising motion is *"weird and disturbing."* Comments also indicate repeated fast movements were considered unsafe. For example, repeated translation of the watch face at high speed *"looks dangerous" (P17)* and *"might cause accidents or harm" (P10)*. Speed received mixed ratings. Participants considered moving slowly more socially acceptable if a movement has to be repeated. However, participants preferred the face to move fast if amplitude is small and/or the movement is not repeated.

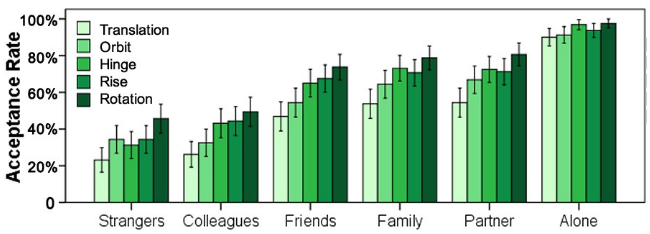

Figure 9. Acceptance rate shown by Audience and Movement. Error bars show ±2 SE

For the question "Are you bothered if these people use face actuation?" there were significant differences in Audience ($\chi^2(4) = 432.97$, $p < 0.001$), Movement ($\chi^2(4) = 142.36$, $p < 0.001$), Speed ($\chi^2(1) = 12.66$, $p < 0.001$), Amplitude ($\chi^2(1) = 189.84$, $p < 0.001$), and Cycle ($\chi^2(1) = 159.39$, $p < 0.001$).

Post-hoc analysis showed significant differences between all pairs of audiences (all $p < 0.05$) except friends and family ($p = 0.17$). Similarly, there were significant differences between all pairs of movements (all $p < 0.05$) except rise and hinge ($p = 0.42$). The trends of all the dependent measures are similar to those observed in Q1. This is interesting, showing that people who feel the social pressure to avoid certain face movements are likely the source of the social pressure. This finding is also promising as we expect to see an increase in social acceptance ratings from both side (e.g. smartwatch owner and audience) after people use it multiple times [58].

Comfort

For ratings of perceived comfort, there was a significant difference for Movement ($\chi^2(4) = 67.95$, $p < 0.001$). Rotation was perceived the most comfortable with a median score of 6 (with 7 being extremely comfortable), followed by hinge and rise (both 5), which received significantly higher ratings than orbit and translation (both 4). Orbit was perceived less comfortable as the watch face may get into the way of the user's hand movement. For example, a participant commented that the watch face might *"hit the table when I am typing" (P6)*. Translating the watch face along the arm was also deemed less comfortable. A participant asked *"if it is going to hurt your arm?" (P9)*. These suggest important considerations in future development of hardware and software applications on an actuated smartwatch.

Discussion

Our findings provide useful insights into the situations where device actuation may not be appropriate due to social pressure. Therefore understanding the context in which the device is used is important for the success of an actuated smartwatch. With the current technologies, it is possible to use the location and calendar events to predict the surrounding audiences. For example, movements should be less restricted if the user is at home with no appointment in the calendar. Despite the accuracy of the prediction algorithm, the user should always be involved in the loop. For example, the system should allow the user to easily start and finish a movement in common smartwatch usage situations (e.g. walking or hands occupied). In the next section, we show the implementation of our input techniques to achieve this goal. Additionally, we demonstrate technical feasibility of actuating the face in a small watch form factor.

CITO PROTOTYPE

To demonstrate the technical feasibility of an actuated watch, we implemented a proof-of-concept prototype (Figure 1) using off-the-shelf electronic components. This section provides our design decisions and implementation details.

Form Factor

Our final prototype is modular. Three modules can be swapped for iterative development of actuation movement mechanisms or to focus on specific combinations of movements. The top module has a 2" TFT serving as the watch display. Each module is 40 by 40 mm with varying thickness. The thickness of all 3 modules together is 33 mm. The thickness is not ideal, but it is constrained enough to test technical feasibility and convey interaction techniques.

Control Box

To achieve this form factor, we place the Arduino DUE main board, DRV8835 motor drivers, Bluetooth module and batteries inside a 110 by 110 by 65 mm plastic control box worn on the upper arm. There are wires for power, ground, and communications connecting the control box to the actuated watch face modules. The control board is wirelessly connected to a laptop using a SparkFun Bluetooth Mate Silver. Custom C# software running on the laptop controlled the actuation remotely and updated the display for demonstrations.

Actuator

There are many options for actuators like shape memory alloys, hydraulics, pneumatics, and motors. Each method has advantages and limitations [59, 70] but the main criteria is size given the form factor. We use Firgelli miniature DC motors for translate, hinge, and orbit. For rotation and rise, we use Gizmoszone GH683S motors which have higher torque. Both gear motors consume 180mW.

Input

Since actuations are output, they would be initiated and controlled primarily by software events (such as a notification arriving). However, the results of study 2 identified the importance for user control of actuation to override or module motions in social situations. We instrumented the watch with a force sensitive sensor so the user can stop the actuation by pressing the display. Since this only works when the other hand is free, we also implemented a one-handed explicit control by tapping the thumb and index finger of the watch hand detected with a Minisense 100 piezo sensor [21]. When one of these stop actions is performed, the face returns to a rest position. Pressure on the screen was measured to detect finger press and in applications where force feedback is provided. Implicit input is provided via the orientation of the watch face, detected using an IMU sensor. Light sensor was used to detect if the watch face is covered by an object.

Modular Actuation Mechanisms

From bottom to top, the three modules are: *orbit-rotate module*, *rise module*, and *hinge-translate module*. The TFT display is mounted on the hinge-translate module on top.

Hinge-translate module

The hinge-translate module has two moving pieces, a sliding piece (hosting the TFT display) used for translation and a hinging piece which can be tilted open from the base of the module (Figure 10a). A motor mounted on the hinging piece engages the gear on the base of the module. Rotating the motor tilts the hinging piece. The sliding piece has two racks. It is actuated using another motor driving a rack-and-pinion mechanism (e.g. linear gear bar) mounted on the inside of the 3D printed case (Figure 10b). The module is 11 mm thick.

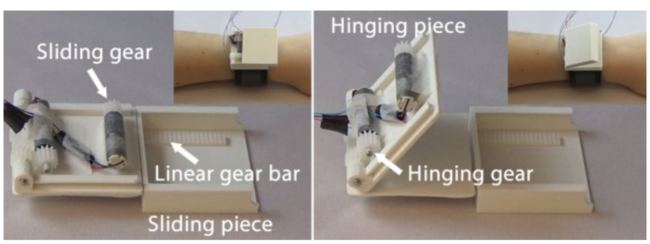

Figure 10. The hinge-translate module

Rise module

The rise module has a moving piece that can be linearly moved up and down from the base of the module. The linear motion was also implemented using the rack and pinion mechanism with the racks mounted on the inner walls of the moving piece (Figure 11). We used two motors to generate an even force on the two sides of the moving piece for smooth movement. In this design, the height of the moving piece determines the amount it can be moved. In our implementation, the module is 14 mm high, sufficient to demonstrate our applications.

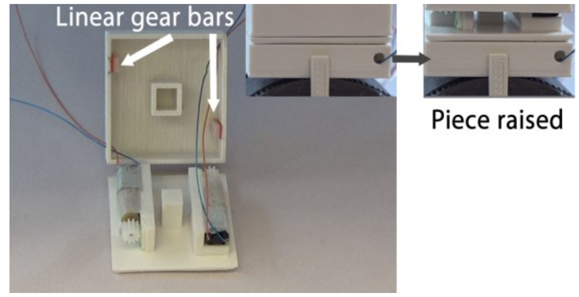

Figure 11. The rise module

Orbit-rotate module

The orbit-rotate module consisted of a rotatory piece that can be rotated on the base of the module, which is attached to a 3D printed wristband. Figure 12a shows the motor that rotates the rotatory piece via a worm drive. Inside the moving piece, there is another motor that drives a pair of gears (engaged with the teeth on the wristband) to orbit the module along the wristband (Figure 12b). The module is 8 mm high.

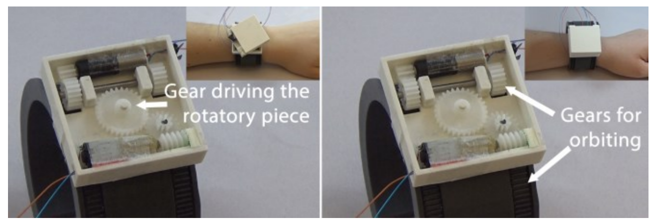

Figure 12. The orbit-rotate module

DEMO APPLICATIONS

We created apps to illustrate how our high-fidelity prototype realizes the proposed interactions in specific applications.

T1 (reorienting face). We used the IMU sensor to detect the orientation of the watch face. If the sensor indicates the watch is not facing upwards, it will orbit around the wristband when an event occurs (e.g. new message) or after a certain time out (e.g. 3 minutes). In principle, the user's eyes could be detected with a computer vision system, enabling the face to hinge also. We leave this for future work.

T2 (hiding inside sleeve) & T3 (escaping sleeve). We used the light sensor to detect if the watch face is covered by a sleeve. If so, the face translates over the back of the hand when a message arrives.

T4a (emergency call) & T4b (mouth movement). Our app can rotate the face, or hinge the face, for different notifications (twist for an emergency call or hinge like a mouth for a lunch appointment). The face can also hinge 180° to tap the back of the user's hand for an urgent notification (Figure 13b).

T5 (notification reminder). We implemented an app, which rotates the watch face off-axis (45°) to notify an event was missed (e.g. phone call) when the watch is not worn. The IMU can sense if the watch is still, indicating it is not worn.

T6 (multi-tasking). We implemented a simulated GPS navigation app, which rotates the watch face to indicate the next turn. The screen content rotates at the same speed in an opposite direction to keep content orientated correctly.

T7 (hinge for sharing). We implemented a sharing app, which hinges the screen 60°on the north side of the watch to easily show the content on the face to someone else. The content flips when the movement finishes.

In the above interactions, a thumb and index finger pinch (sensed by a piezo sensor) stops the movement, or returns the face to the rest position.

T8 (haptic force buttons). We implemented two haptic buttons (e.g. Accept and Decline) to demonstrate haptic force feedback (Figure 13a). The Decline button must be pressed more firmly than the Accept button for eyes-free verification feedback. The screen rises to show the buttons, then it reacts with a fast lowering movement when Accept is pressed lightly and a slow movement when Decline is pressed firmly. A pressure sensor detects pressing force. Once pushed down to its rest position, the button command is triggered.

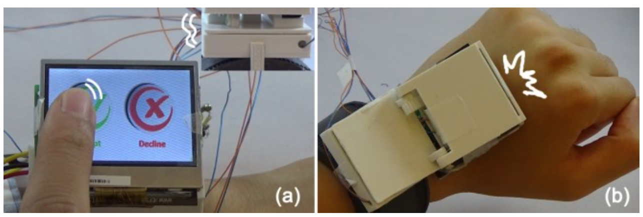

Figure 13. Haptics: (a) haptic Accept and Decline buttons; (b) hinging to tap the back of hand to get the user's attention.

DISCUSSION AND LIMITATIONS

We discuss insights gained from this investigation and acknowledge current limitations.

Context Sensing and Input. Our focus has been on output, but an actuated smartwatch relies on context sensing to detect the wearers activities, audiences, and environment to avoid social embarrassment and best serve their needs. There exists a rich body of research in sensing context-awareness using GPS, calendar, acoustics, etc. We thus leave it outside the scope of this work. Our current implementation uses simple light and IMU sensors that have false positives. We did not thoroughly explore input techniques. Future research is should examine what input is needed for actuation and how it can be made most effective.

Hardware Prototype Evaluation. Our studies used low-fidelity prototypes, which were effective in answering fundamental questions independent of implementation constraints. Our high-fidelity prototype demonstrates technical methods, but we have not evaluated it with users. This is partly because the mechanisms are not robust enough for unexpected actions during a study and partly because the size and external control box may introduce confounding factors that make measuring aspects like usability difficult. We will look into alternative ways for actuating and sensing part displacement to reduce the form factor. A second, or third generation device would likely overcome the current issues and enable an accurate user evaluation. One exciting avenue is to investigate social acceptability with a future device deployed in real-world environments and scenarios.

Mechanical Constraints. There are limitations due to our mechanical implementation. Translation is limited by the width of the watch face and rising is limited by the thickness of the face. A telescoping rack mechanism (like power antennas) would extend this amplitude. We use a single mechanical hinge, which means the face must rotate to hinge in a specific direction. This can be resolved with more complex mechanisms demonstrated in previous work [60].

Physical Constraints. The current implementation is limited in sensing the physical constraints in the surrounding environment. Some techniques may not work well due to physical constraints. For example, the face may get stuck if the sleeve is tight. Rising or translating could accidently hit the hand or nearby objects. The current implementation uses a proximity sensor to detect if the watch is covered by sleeve so that lift can be disabled. Future research will explore more sensing techniques to detect potential obstructions nearby.

Size. Our implementation is bulky and requires and external control box. We expect all components can be integrated into the watch with further engineering effort. The actuation mechanism size can be reduced using custom high precision miniature gears and motors. For example, using ultra-sonic motors would significantly reduce device thickness.

Shape. The shape of the face influences interaction, actuation, and affordance. For example, if the watch face is circular, it can be continuously rolled around the band. This enables a new set of interactions and challenges for actuation. Future research will explore different shapes.

CONCLUSION

In this paper, we presented Cito, a smartwatch that can move its face in five ways: rotation, hinge, translation, rising, and orbiting around the wrist. We describe how these movements enable new interactions unavailable in the current smartwatches. Using videos of a low-fidelity prototype, we validated the usefulness of the idea for solving problems caused by a fixed smartwatch face. A second user study, provide insight into situations where certain face movements need to be avoided due to social acceptability and comfort. Based on the study results, we developed a high fidelity prototype using a LCD display and a modular mechanical system supporting all five face movements using gear motors. This prototype demonstrates the feasibility of the proposed approach.

We explored only a small subset of possible face movements. For example, the face can be rotated in an axis off the center of the watch, or non-rigid movements like bending and curls could be explored. These would enable even larger movement vocabularies, and the methodology described above could investigate, validate, and demonstrate those movements as well. We recognize our work investigates a radical idea, but our hope is that we also show how a methodical and principled approach can explore any such radical visions.

REFERENCES

1. Aria Wearable, https://www.ariawearable.com/
2. Flexible SmartWatch display by SmartSound Case Inc, http://www.smartsoundcase.com/portfolio-view/flexible-smartwatch-display-by-smartsound-case-inc/
3. Kenxingda Smartwatch Phone, http://www.kenxinda.com/
4. Lenovo's Magic View Smartwatch, https://www.engadget.com/2015/05/28/lenovo-magic-view-concept-smartwatch/
5. Lenovo flexible Phone, https://www.cnet.com/news/lenovos-flexible-phone-bends-around-your-wrist/
6. Jason Alexander, Andres Lucero, and Sriram Subramanian. 2012. Tilt displays: designing display surfaces with multi-axis tilting and actuation. In *Proceedings of the 14th international conference on Human-computer interaction with mobile devices and services* (MobileHCI'12), 161-170. DOI=http://dx.doi.org/10.1145/2371574.2371600
7. Brian Amento, Will Hill, and Loren Terveen. 2002. The sound of one hand: a wrist-mounted bio-acoustic fingertip gesture interface. In *CHI '02 Extended Abstracts on Human Factors in Computing* Systems (CHI EA '02), 724-725. DOI=http://dx.doi.org/10.1145/506443.506566
8. Daniel Ashbrook, Kent Lyons, and Thad Starner. 2008. An investigation into round touchscreen wristwatch interaction. In *Proceedings of the 10th international conference on Human-computer interaction with mobile devices and services* (MobileHCI'08), 311-314. DOI=http://dx.doi.org/10.1145/1409240.1409276
9. Gabor Blasko and Steven Feiner. 2004. An Interaction System for Watch Computers Using Tactile Guidance and Bidirectional Segmented Strokes. In *Proceedings of the Eighth International Symposium on Wearable Computers* (ISWC '04), 120-123. DOI=http://dx.doi.org/10.1109/ISWC.2004.6
10. Jeffrey R Blum, Ilja Frissen, and Jeremy R Cooperstock. 2015. Improving Haptic Feedback on Wearable Devices through Accelerometer Measurements. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology* (UIST'15), 31-36. DOI=http://dx.doi.org/10.1145/2807442.2807474
11. Jesse Burstyn, Paul Strohmeier, and Roel Vertegaal. 2015. DisplaySkin: Exploring Pose-Aware Displays on a Flexible Electrophoretic Wristband. In *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction* (TEI'15), 165-172. DOI=http://dx.doi.org/10.1145/2677199.2680596
12. Liwei Chan, Yi-Ling Chen, Chi-Hao Hsieh, Rong-Hao Liang, and Bing-Yu Chen. 2015. CyclopsRing: Enabling Whole-Hand and Context-Aware Interactions Through a Fisheye Ring. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology* (UIST'15), 549-556. DOI=http://dx.doi.org/10.1145/2807442.2807450
13. Xiang 'Anthony' Chen, Tovi Grossman, Daniel J. Wigdor, and George Fitzmaurice. 2014. Duet: exploring joint interactions on a smart phone and a smart watch. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI'14), 159-168. DOI=http://dx.doi.org/10.1145/2556288.2556955
14. Andrew Crossan, John Williamson, Stephen Brewster, and Rod Murray-Smith. 2008. Wrist rotation for interaction in mobile contexts. In *Proceedings of the 10th international conference on Human computer interaction with mobile devices and services* (MobileHCI'08), 435-438. DOI=http://dx.doi.org/10.1145/1409240.1409307
15. Artem Dementyev, Hsin-Liu Kao, Inrak Choi, Deborah Ajilo, Maggie Xu, Joseph A. Paradiso, Chris Schmandt, and Sean Follmer. 2016. Rovables: Miniature On-Body Robots as Mobile Wearables. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology* (UIST'16), 111-120. DOI=https://doi.org/10.1145/2984511.2984531
16. Artem Dementyev and Joseph A. Paradiso. 2014. WristFlex: low-power gesture input with wrist-worn pressure sensors. In *Proceedings of the 27th annual ACM symposium on User interface software and technology* (UIST'14), 161-166. DOI=http://doi.acm.org/10.1145/2642918.2647396
17. Panteleimon Dimitriadis and Jason Alexander. 2014. Evaluating the effectiveness of physical shape-change for in-pocket mobile device notifications. In *Proceedings of the 32nd annual ACM conference on Human factors in computing systems* (CHI'14), 2589-2592. DOI=http://dx.doi.org/10.1145/2556288.2557164
18. Sean Follmer, Daniel Leithinger, Alex Olwal, Akimitsu Hogge, and Hiroshi Ishii, 2013. inFORM: dynamic physical affordances and constraints through shape and object actuation. In *Proceedings of the 26th annual ACM symposium on User interface software and technology* (UIST'13), 417-426. DOI=http://dx.doi.org/10.1145/2501988.2502032
19. Rui Fukui, Masahiko Watanabe, Tomoaki Gyota, Masamichi Shimosaka, and Tomomasa Sato. 2011. Hand shape classification with a wrist contour sensor: development of a prototype device. In *Proceedings of the 13th international conference on Ubiquitous computing* (UbiComp'11), 311-314. DOI=http://dx.doi.org/10.1145/2030112.2030154
20. Antonio Gomes, Andrea Nesbitt, and Roel Vertegaal. 2013. MorePhone: a study of actuated shape deformations for flexible thin-film smartphone notifications. In *Proceedings of the SIGCHI Conference on Human*

Factors in Computing Systems (CHI'13), 583-592. DOI=http://dx.doi.org/10.1145/2470654.2470737

21. Jun Gong, Xing-Dong Yang, and Pourang Irani. 2016. WristWhirl: One-handed Continuous Smartwatch Input using Wrist Gestures. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology* (UIST'16), 861-872. DOI=https://doi.org/10.1145/2984511.2984563
22. Chris Harrison and Scott E. Hudson. 2009. Abracadabra: wireless, high-precision, and unpowered finger input for very small mobile devices. In *Proceedings of the 22nd annual ACM symposium on User interface software and technology* (UIST'09), 121-124. DOI=http://dx.doi.org/10.1145/1622176.1622199
23. Chris Harrison, Desney S. Tan, and Dan Morris. 2010. Skinput: appropriating the body as an input surface. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems Computer Human Interaction* (CHI'10), 453-462. DOI=http://dx.doi.org/10.1145/1753326.1753394
24. Fabian Hemmert. 2008. Ambient Life: Permanent Tactile Life-like Actuation as a Status Display in Mobile Phones. In *Adjunct Proc. of the 21st annual ACM symposium on User Interface Software and Technology* (UIST AP'08).
25. Fabian Hemmert, Susann Hamann, Matthias Löwe, Anne Wohlauf, and Gesche Joost. 2010. Shape-changing mobiles: tapering in one-dimensional deformational displays in mobile phones. In *Proceedings of the fourth international conference on Tangible, embedded, and embodied interaction* (TEI'10), 249-252. DOI=http://dx.doi.org/10.1145/1709886.1709936
26. Fabian Hemmert, Matthias Löwe, Anne Wohlauf, and Gesche Joost. 2013. Animate mobiles: proxemically reactive posture actuation as a means of relational interaction with mobile phones. *In Proceedings of the 7th International Conference on Tangible, Embedded and Embodied Interaction* (TEI'13), 267-270. DOI=http://dx.doi.org/10.1145/2460625.2460669
27. Alexandra Ion, Edward Jay Wang, and Patrick Baudisch. 2015. Skin Drag Displays: Dragging a Physical Tactor across the User's Skin Produces a Stronger Tactile Stimulus than Vibrotactile. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (CHI'15), 2501-2504. DOI=http://dx.doi.org/10.1145/2702123.2702459
28. Hiroo Iwata, Hiroaki Yano, Fumitaka Nakaizumi, and Ryo Kawamura. 2001. Project FEELEX: adding haptic surface to graphics. In *Proceedings of the 28th annual conference on Computer graphics and interactive techniques* (SIGGRAPH'01), 469-476. DOI=http://dx.doi.org/10.1145/383259.383314
29. Frederic Kerber, Pascal Lessel, Antonio Kr, #252, and ger. 2015. Same-side Hand Interactions with Arm-placed Devices Using EMG. In *Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems* (CHI EA'15), 1367-1372. DOI=http://dx.doi.org/10.1145/2702613.2732895
30. Jungsoo Kim, Jiasheng He, Kent Lyons, and Thad Starner. 2007. The Gesture Watch: A Wireless Contact-free Gesture based Wrist Interface. In *Proceedings of the 2007 11th IEEE International Symposium on Wearable Computers* (ISWC '07), 1-8. DOI=http://dx.doi.org/10.1109/ISWC.2007.4373770
31. Byron Lahey, Audrey Girouard, Winslow Burleson, and Roel Vertegaal. 2011. PaperPhone: understanding the use of bend gestures in mobile devices with flexible electronic paper displays. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI'11), 1303-1312. DOI=http://dx.doi.org/10.1145/1978942.1979136
32. Gierad Laput, Robert Xiao, Xiang 'Anthony' Chen, Scott E. Hudson, and Chris Harrison. 2014. Skin buttons: cheap, small, low-powered and clickable fixed-icon laser projectors. In *Proceedings of the 27th annual ACM symposium on User interface software and technology* (UIST'14), 389-394. DOI=http://dx.doi.org/10.1145/2642918.2647356
33. Jaeyeon Lee and Geehyuk Lee. 2016. Designing a Non-contact Wearable Tactile Display Using Airflows In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology* (UIST'16), 183-194. DOI=https://doi.org/10.1145/2984511.2984583
34. Seungyon "Claire" Lee and Thad Starner. 2010. BuzzWear: alert perception in wearable tactile displays on the wrist. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI'10), 433-442. DOI=http://dx.doi.org/10.1145/1753326.1753392
35. Daniel Leithinger, Sean Follmer, Alex Olwal, and Hiroshi Ishii. 2014. Physical telepresence: shape capture and display for embodied, computer-mediated remote collaboration. In *Proceedings of the 27th annual ACM symposium on User interface software and technology* (UIST'14), 461-470. DOI=http://dx.doi.org/10.1145/2642918.2647377
36. Daniel Leithinger, David Lakatos, Anthony DeVincenzi, Matthew Blackshaw, and Hiroshi Ishii. 2011. Direct and gestural interaction with relief: a 2.5 D shape display. In *Proceedings of the 24th annual ACM symposium on User interface software and technology* (UIST'11), 541-548. DOI=http://dx.doi.org/10.1145/2047196.2047268
37. Christian Loclair, Sean Gustafson, and Patrick Baudisch. 2010. PinchWatch: a wearable device for one-

handed microinteractions. In *12th International Conference on Human Computer Interaction with Mobile Devices and Services* (MobileHCI'10).

38. Kent Lyons, David Nguyen, Daniel Ashbrook, and Sean White. 2012. Facet: a multi-segment wrist worn system. In *Proceedings of the 25th annual ACM symposium on User interface software and technology* (UIST'12), 123-130. DOI=http://dx.doi.org/10.1145/2380116.2380134
39. Heiko Muller, Andreas Locken, Wilko Heuten, and Susanne Boll. 2014. Sparkle: an ambient light display for dynamic off-screen points of interest. In *Proceedings of the 8th Nordic Conference on Human-Computer Interaction: Fun, Fast, Foundational* (NordiCHI'14), 51-60. DOI=http://dx.doi.org/10.1145/2639189.2639205
40. Mark Marshall, Thomas Carter, Jason Alexander, and Sriram Subramanian. 2012. Ultra-tangibles: creating movable tangible objects on interactive tables. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI'12), 2185-2188. DOI=https://doi.org/10.1145/2207676.2208370
41. Ken Nakagaki, Sean Follmer, and Hiroshi Ishii. 2015. LineFORM: Actuated Curve Interfaces for Display, Interaction, and Constraint. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology* (UIST'15), 333-339. DOI=http://dx.doi.org/10.1145/2807442.2807452
42. Ken Nakagaki, Luke Vink, Jared Counts, Daniel Windham, Daniel Leithinger, Sean Follmer, and Hiroshi Ishii. 2016. Materiable: Rendering Dynamic Material Properties in Response to Direct Physical Touch with Shape Changing Interfaces. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (CHI'16), 2764-2772. DOI=https://doi.org/10.1145/2858036.2858104
43. Diana Nowacka, Karim Ladha, Nils Y. Hammerla, Daniel Jackson, Cassim Ladha, Enrico Rukzio, and Patrick Olivier. 2013. Touchbugs: actuated tangibles on multi-touch tables. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI'13), 759-762. DOI=http://dx.doi.org/10.1145/2470654.2470761
44. Ian Oakley and Doyoung Lee. 2014. Interaction on the edge: offset sensing for small devices. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI'14), 169-178. DOI=http://dx.doi.org/10.1145/2556288.2557138
45. Simon Olberding, Kian Peen Yeo, Suranga Nanayakkara, and Jurgen Steimle. 2013. AugmentedForearm: exploring the design space of a display-enhanced forearm. In *Proceedings of the 4th Augmented Human International Conference* (AH'13), 9-12. DOI=http://dx.doi.org/10.1145/2459236.2459239
46. Santiago Ortega-Avila, Bogdana Rakova, Sajid Sadi, and Pranav Mistry. 2015. Non-invasive optical detection of hand gestures. In *Proceedings of the 6th Augmented Human International Conference* (AH'15), 179-180. DOI=http://dx.doi.org/10.1145/2735711.2735801
47. Jefferson Pardomuan, Toshiki Sato, and Hideki Koike. 2013. LivingClay: particle actuation to control display volume and stiffness. In *Proceedings of the adjunct publication of the 26th annual ACM symposium on User interface software and technology* (UIST'13), 103-104. DOI=http://dx.doi.org/10.1145/2508468.2514731
48. Joohee Park, Young-Woo Park, and Tek-Jin Nam. 2014. Wrigglo: shape-changing peripheral for interpersonal mobile communication. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI'14), 3973-3976. DOI=http://dx.doi.org/10.1145/2559206.2574783
49. Young-Woo Park, Joohee Park, and Tek-Jin Nam. 2015. The trial of bendi in a coffeehouse: use of a shape-changing device for a tactile-visual phone conversation. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (CHI'15), 2181-2190. DOI=http://dx.doi.org/10.1145/2702123.2702326
50. Jerome Pasquero, Scott J. Stobbe, and Noel Stonehouse. 2011. A haptic wristwatch for eyes-free interactions. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI'11), 3257-3266. DOI=http://dx.doi.org/10.1145/1978942.1979425
51. James Patten and Hiroshi Ishii. 2007. Mechanical constraints as computational constraints in tabletop tangible interfaces. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI'07), 809-818. DOI=http://dx.doi.org/10.1145/1240624.1240746
52. Esben W Pedersen, Sriram Subramanian, and Kasper Hornbæk. 2014. Is my phone alive?: a large-scale study of shape change in handheld devices using videos. In *Proceedings of the 32nd annual ACM conference on Human factors in computing systems* (CHI'14), 2579-2588. DOI=http://dx.doi.org/10.1145/2556288.2557018
53. Esben Warming Pedersen and Kasper Hornbaek. 2011. Tangible bots: interaction with active tangibles in tabletop interfaces. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI'11), 2975-2984. DOI=http://dx.doi.org/10.1145/1978942.1979384
54. Simon T. Perrault, Eric Lecolinet, James Eagan, and Yves Guiard. 2013. Watchit: simple gestures and eyes-

free interaction for wristwatches and bracelets. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI'13), 1451-1460. DOI=http://dx.doi.org/10.1145/2470654.2466192

55. Ioannis Politis, Stephen Brewster, and Frank Pollick. 2015. To Beep or Not to Beep?: Comparing Abstract versus Language-Based Multimodal Driver Displays. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing System*s (CHI'15), 3971-3980. DOI=http://dx.doi.org/10.1145/2702123.2702167
56. Ivan Poupyrev, Tatsushi Nashida, and Makoto Okabe. 2007. Actuation and Tangible User Interfaces: the Vaucanson Duck. Robots, and Shape Displays, In *Proceedings of the 1st international conference on Tangible and embedded interaction* (TEI' 07), 205-212. DOI=http://dx.doi.org/10.1145/1226969.1227012
57. Jun Rekimoto. 2001. GestureWrist and GesturePad: Unobtrusive Wearable Interaction Devices. In *Proceedings of the 5th IEEE International Symposium on Wearable Computers*, 21. DOI=http://dx.doi.org/10.1109/ISWC.2001.962092
58. Julie Rico and Stephen Brewster. 2010. Usable Gestures for Mobile Interfaces: Evaluating Social Acceptability. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI'10), 887-896. DOI=http://dx.doi.org/10.1145/1753326.1753458
59. Anne Roudaut, Abhijit Karnik, Markus Löchtefeld, and Sriram Subramanian. 2013. Morphees: toward high shape resolution in self-actuated flexible mobile devices. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI'13), 593-602. DOI=http://dx.doi.org/10.1145/2470654.2470738
60. Anne Roudaut, Diana Krusteva, M McCoy, A Karnik, Karthik Ramani, and Sriram Subramanian. 2016. Cubimorph: designing modular interactive devices. In *2016 IEEE International Conference on Robotics and Automation (ICRA) IEEE, 3339-3345.* DOI=http://dx.doi.org/10.1109/ICRA.2016.7487508
61. T. Scott Saponas, Desney S. Tan, Dan Morris, Ravin Balakrishnan, Jim Turner, and James A. Landay. 2009. Enabling always-available input with muscle-computer interfaces. In *Proceedings of the 22nd annual ACM symposium on User interface software and technology* (UIST'09), 167-176. DOI=http://dx.doi.org/10.1145/1622176.1622208
62. Carsten Schwesig, Ivan Poupyrev, and Eijiro Mori. 2004. Gummi: a bendable computer. In *Proceedings of the SIGCHI conference on Human factors in computing systems* (CHI'04), 263-270. DOI=http://dx.doi.org/10.1145/985692.985726
63. Teddy Seyed, Xing-Dong Yang, and Daniel Vogel. 2016. Doppio: A Reconfigurable Dual-Face Smartwatch for Tangible Interaction. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (CHI'16), 4675-4686. DOI=https://doi.org/10.1145/2858036.2858256
64. Mike Sinclair, Michel Pahud, and Hrvoje Benko. 2013. TouchMover: actuated 3D touchscreen with haptic feedback. In *Proceedings of the 2013 ACM international conference on Interactive tabletops and surfaces*, 287-296. DOI=http://dx.doi.org/10.1145/2512349.2512805
65. Paul Strohmeier, Roel Vertegaal, and Audrey Girouard. 2012. With a flick of the wrist: stretch sensors as lightweight input for mobile devices. In *Proceedings of the Sixth International Conference on Tangible, Embedded and Embodied Interaction* (TEI'12), 307-308. DOI=http://dx.doi.org/10.1145/2148131.2148195
66. Faisal Taher, John Hardy, Abhijit Karnik, Christian Weichel, Yvonne Jansen, Kasper Hornbæk, and Jason Alexander. 2015. Exploring interactions with physically dynamic bar charts. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (CHI'15), 3237-3246. DOI=http://dx.doi.org/10.1145/2702123.2702604
67. Malte Weiss, Florian Schwarz, Simon Jakubowski, and Jan Borchers. 2010. Madgets: actuating widgets on interactive tabletops. In *Proceedings of the 23nd annual ACM symposium on User interface software and technology* (UIST'10), 293-302. DOI=http://dx.doi.org/10.1145/1866029.1866075
68. Robert Xiao, Gierad Laput, and Chris Harrison. 2014. Expanding the input expressivity of smartwatches with mechanical pan, twist, tilt and click. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI'14), 193-196. DOI=http://dx.doi.org/10.1145/2556288.2557017
69. Shota Yamanaka and Homei Miyashita. 2014. Vibkinesis: notification by direct tap and'dying message'using vibronic movement controllable smartphones. In *Proceedings of the 27th annual ACM symposium on User interface software and technology* (UIST'14), 535-540. DOI=http://dx.doi.org/10.1145/2642918.2647365
70. Lining Yao, Ryuma Niiyama, Jifei Ou, Sean Follmer, Clark Della Silva, and Hiroshi Ishii. 2013. PneUI: Pneumatically actuated soft composite materials for shape changing interfaces. In *Proceedings of the 26th annual ACM symposium on User interface software and technology* (UIST'13), 13-22. DOI=http://dx.doi.org/10.1145/2501988.2502037
71. Sang Hyun YOO, Yo Han ROH, Ji Hyun LEE, Ho Dong LEE, and HONG Seok Jin. 2015. Smart Watch and Control Method Thereof, L. Samsung Electronics Co. Ed.
72. Yang Zhang and Chris Harrison. 2015. Tomo: Wearable, Low-Cost Electrical Impedance Tomography for Hand Gesture Recognition. In *Proceedings of the 28th*

Annual ACM Symposium on User Interface Software and Technology (UIST'15), 167-173. DOI=http://dx.doi.org/10.1145/2807442.2807480

73. Yang Zhang, Junhan Zhou, Gierad Laput, and Chris Harrison. 2016. SkinTrack: Using the Body as an Electrical Waveguide for Continuous Finger Tracking on the Skin. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (CHI'16), 1491-1503. DOI=https://doi.org/10.1145/2858036.2858082