

RetroShape: Leveraging Rear-Surface Shape Displays for 2.5D Interaction on Smartwatches

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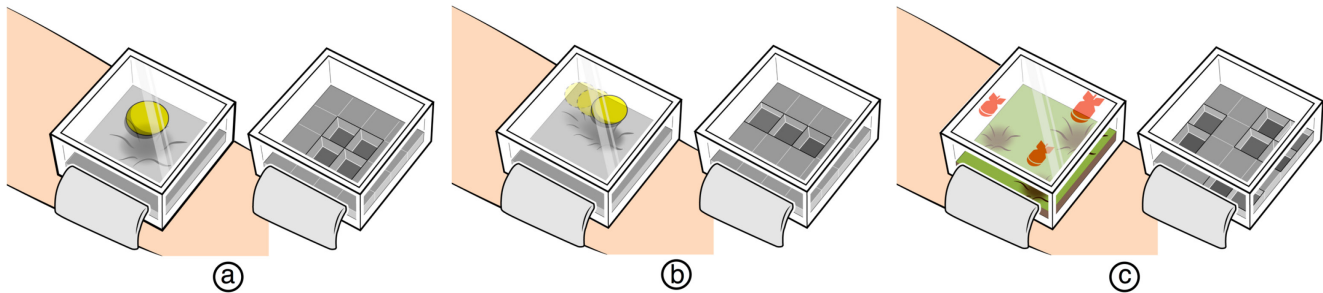


Figure 1. RetroShape aims to extend the visual scene to 2.5D physical space by a deformable display on its rear surface. Our RetroShape prototype equips 4×4 taxels, which can simulate (a) a bouncing ball on an elastic surface, (b) ball rolling, or (c) multiple strikes on the ground.

ABSTRACT

The small screen size of a smartwatch limits user experience when watching or interacting with media. We propose a supplementary tactile feedback system to enhance the user experience with a method unique to the smartwatch form factor. Our system has a deformable surface on the back of the watch face, allowing the visual scene on screen to extend into 2.5D physical space. This allows the user to watch and feel virtual objects, such as experiencing a ball bouncing against the wrist. We devised two controlled experiments to analyze the influence of tactile display resolution on the illusion of virtual object presence. Our first study revealed that on average, a taxel can render virtual objects between 70% and 138% of its own size without shattering the illusion. From the second study, we found visual and haptic feedback can be separated by 4.5mm to 16.2mm for the tested taxels. Based on the results, we developed a prototype (called RetroShape) with 4×4 10mm taxels using micro servo motors, and demonstrated its unique capability through a set of tactile-enhanced games and videos. A preliminary user evaluation showed that participants welcome RetroShape as a useful addition to existing smartwatch output.

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INTRODUCTION

Smartwatches provide quick access to short-time entertainment applications, especially when users are on-the-move, e.g. in a bus or train. However, user experience in such applications is limited due to the small screen area and limited input and output options. While smartwatch visual and auditory technologies have improved substantially, the potential of smartwatch-enabled haptics in video and game applications remains to be exploited.

We leverage the user’s skin under the watch face for sensing haptic output with collocated visual content. Our approach enhances the viewing experience on a smartwatch using a shape-changing tactile display on the rear surface of the smartwatch. Each pixel on the screen has a corresponding tactile pixel (or *taxel*) on the back of the watch face, allowing the virtual world to be extended to the 2.5D physical space on its back. With this approach, users can feel virtual objects or events happening on screen (e.g. ball bouncing against the wrist) on their skin under the smartwatch. In contrast to existing approaches such as vibrotactile [18, 19, 24], skin-drag [9], or haptic edge displays [12], the proposed approach uses a shape-changing surface on the back of the smartwatch to simulate the location, size, shape, and motion of the virtual objects shown on the screen (Figure 1). This type of immersive experience is unique to smartwatches.

This new type of haptic output requires pixels on the screen to be coupled with a collocated taxel on the back. This allows users to feel an enhanced sense of presence for virtual objects. Ideally, the visual and tactile shape displays have the same resolution to realistically render fine-grained tactile feelings (e.g. the wrist stabbed by a zombie). However, the resolution of the taxel display can be lower depending on designer needs or hardware implementation. We conducted two studies to understand the trade-off introduced by different taxel resolutions. In the first study, we investigate how similar the size of visual and tactile stimuli need to be matched in order to maintain a realistic visual-haptic feeling. In particular, we used an adaptive stair case procedure to find the acceptable size ranges of visual objects for three taxel resolutions with taxel size ranging from 2mm to 10mm. The result revealed that, on average, a taxel can render virtual objects between 70% and 138% of its own size without shattering the illusion. In the second study, we investigated how tightly the location of the visual and tactile stimuli need to be matched. The result showed that the visual and tactile feedback do not need to be collocated. However, the smaller the taxel is the larger distance the tactile and visual feedback can be separated. In particular, we found that the largest distances between visual and tactile feedback are 4.5mm, 11.8mm, and 16.2mm for 10mm, 6mm, and 2mm taxels respectively. These results provide insights for designers creating applications for the taxel display on smartwatches.

Finally, to investigate technical challenges and demonstrate interaction techniques, we developed a hardware prototype (called RetroShape) composed of a 2" TFT display and a 4×4 pin array, actuated using 16 miniature servo motors (see Figure 4). The proof-of-concept prototype was used in a preliminary user evaluation to gain feedback on deformable surface tactile-enabled smartwatches.

Our primary contributions are: (1) the notion of a tactile surface on the back of a smartwatch; (2) the results of two user studies that investigate the influence of taxel display resolution on user illusion; (3) the implementation of RetroShape, a proof-of-concept prototype; (4) a set of usage applications to demonstrate the RetroShape's unique capabilities; (5) the result of a preliminary user evaluation.

RELATED WORK

Many researchers have studied forms of haptic feedback in mobile interfaces. We present the existing literature in cutaneous haptic interfaces with a focus on vibrotactile feedback, force feedback, and shape-changing displays. Compressive reviews in haptics can be found in [3, 37, 44].

Vibrotactile Feedback

Vibrotactile feedback is a common cutaneous haptic stimulation and has been widely used in VR [45] and game applications to simulate physical impact (e.g. PS, Xbox game controller). Aside from simply vibrating the skin in different locations, multiple vibrators can be used to simulate moving strokes. For example, Tactile Brush [10] uses a grid of vibrators on the back of a chair to generate two dimensional tactile

moving strokes to simulate scenes like explosions, drops, or collisions. While vibrotactile devices are cheap and easy to build, vibrating the skin feels different than tapping or pressing with a certain amount of force [16]. This is because vibration is sensed using Pacinian Corpuscle (FA II), whereas force is sensed mainly using Merkel Receptor (SA I). It is thus known that vibration alone is insufficient in applications requiring realistic haptic feeling to simulate physical impact. As shown in many applications, vibrotactile feedback is often coupled with force feedback to provide more immersive haptic experience [14, 15]. We focus on taxel display as a mechanism to stimulate physical impact. We do not use vibrotactile in this work but it can be a good addition in many situations.

Aside from simulating physical impact, a large body of research has also been focused on using vibrotactile for communicating messages to the users. For example, Pasquero et al. used the vibrotactile stimulation to deliver temporal notifications to smartwatch users [34]. Tactons [6] uses a matrix of miniature vibrators to haptically display Braille-like messages on the fingertip. In smartwatch applications, vibrator arrays were used to communicate with the users using shapes [19, 28], strokes [18, 20], and alphanumeric patterns [24]. OmniVib [1] further extends the techniques to be used in the different locations of body, an effective way for motor skill training [26, 29, 33, 38, 41].

Force Feedback

Vibration can also be used to generate tangential force on the skin. For example, piezo tactile displays have been used to create a stretch feeling on a moving fingertip to simulate textures like bumps or gratings [27, 36]. Bau et al. [2] uses the electro-vibration technology to let the users feel the frictions of different virtual surfaces on a touchscreen. In the VR environment, miniature motors have been used to create a shear force on the fingertip to simulate the friction [3, 47]. Kim et al.'s finger-worn device can generate a normal force to the fingertip to simulate the finger touching a hard surface [13]. The limitation of this approach is that it is essentially a single-pixel shape display [4], which lacks the ability to render complex shapes and textures of the virtual objects. The same limitation exists in mid-air force feedback techniques, which transmit the force through the air using air vortexes [40] or ultrasonic waves [7].

Force feedback can be also provided by dragging the user's skin. Work in this type of force feedback has been primarily focused on communicating notifications to the users. For example, Skin Drag Display [9] and tactoRing [39] use a moving vibrator to drag the user's skin to send simple messages to the users.

Shape-Changing Displays

This class of work involves a matrix of mechanically actuated pins to render the shape or texture of the virtual objects. Small devices like [5, 43] were developed to simulate fine-grained textures on the fingertip. The technology lacks the ability to display visual contents over the haptic feeling. On the other hand, tabletop systems [11,

35] have collocated visual and shape displays (often with much lower resolution). Project FEELEX [11], for example, has taxels beneath a flexible surface, allowing users to see, touch, and feel the shape of the projected graphics. Lumen [35] is a similar system, which has a low resolution visual display made of physical pixels that can be actuated vertically. Follmer et al. demonstrated that the shape displays can also be used to provide dynamic affordance for the users to interact with virtual and physical objects [8]. A follow-up work extended the concept to tele-presence and collaborative work [22].

Aside from tabletops, the shape displays have also been used in the handheld platforms and in VR applications. For example, Haptic Edge Display [12] uses a one-dimensional taxel array on the edge of a smartphone to create dynamic affordance for various applications. TextureTouch [4] is a handheld controller composed of a 4×4 taxels, designed to haptically display the texture and shape of virtual objects on the fingertip in a VR environment. In the wearable context, most work in shape changing devices has been focused on novel interactions rather than haptic experiences. For example, LineFORM [31] and PneuUI [46] were created to provide new ways for the users to interact with wrist-worn devices while other work [21, 25] demonstrate the benefit of shape changing to assist physical activities.

None of the existing work studies shape display as a mechanism to enrich the haptic experience for entertainment applications on smartwatches. Additionally, unlike the existing systems [11, 35], where pixels and taxels overlaps, having a shape display on the rear surface of a smartwatch introduces new technical challenges and human factor questions, one of which for example, is the coupling of pixels and taxels to create a strong illusion of the presence of virtual objects or events. As such, shape display resolution may affect the level of fidelity.

TAXEL DISPLAY CAPABILITIES

A taxel display can simulate the physical shape and geometry of the virtual objects shown on screen through the rear-surface of the watch. This allows users to see and feel the virtual object at the same time. Like the existing devices [11, 35], the shape display can render and control size, shape, location, and texture parameters. The motion of the object can also be rendered through a set of dynamic parameters, such as object movements in the x,y,z directions, rotation, tilting, or change in size. We explore the design space of the taxel display in this section.

C1: Size of the object. Virtual objects may be rendered in different sizes, so when they ‘touch’ the skin, the taxels under the object contact area need to raise to give the wearer the sense of size of the object.

C2: Shape of the object. The shape of the virtual object can also be rendered haptically in a 2.5D space to create a realistic feeling for the presence of the object.

C3: Location of the object. The presence of a virtual object in a certain location can be haptically rendered by raising the taxels in the same location to create a feeling that the object resides on the user’s wrist.

C4: Number of the objects. When there are multiple objects shown on the screen (e.g. asteroid rain hits the earth), they need to haptically simulated in multiple locations.

C5: Texture of the object. The texture of different objects can also be rendered haptically. For example the skin of a dinosaur can be rendered rough and eggshell can be rendered smooth.

C6: Motion of the object. Similar to [8], different motions of the visual object (e.g. movement, tilting angle, and change in size or shape) can be haptically rendered by sequentially actuating the taxels.

C7: Material properties. Using the method described in [32], different material properties (e.g. surface stiffness or elasticity) can also be rendered haptically on the wrist.

C8: Pressure. Pressure can also be haptically rendered using a shape display. Heavy objects can be rendered using higher pressure than light objects. Different levels of pressure can be created by controlling the taxel’s traveling distance into the skin.

TAXEL DISPLAY RESOLUTION CONSIDERATIONS

The taxel display relies on the Merkel receptor (SA-I) in the skin to sense pressure and (coarse) texture information. The degree of realism is coupled to the resolution of the taxel display in the x,y,z axes. A high resolution is preferred to guarantee that haptic scenes can be rendered in sufficient precision. Ideally, the taxel and pixel displays have the same resolution with each taxel paired with a pixel in the same location on the screen. This allows the taxel display to haptically render objects and events most realistically. Examples range from a Ping-Pong ball bouncing on the skin, a dragonfly landing on the wrist, or a sharp arrowhead stabbing the skin. However, there are trade-offs introduced by high and low resolutions. For example, designing and developing the actuation mechanism for a high resolution taxel display in a compact form factor is challenging. Power consumption is another issue when thousands of taxels need to be actuated. In contrast, low resolution displays mitigate these issues.

In theory, the sense of illusion can be preserved despite using a lower resolution taxel display since a human’s arm and wrist are not sensitive to fine-grained tactile stimuli [48]. However, none of the existing literature provides an insight into the trade-off introduced by different taxel resolutions with respect to the ability to realistically render the aforementioned parameters (e.g. C1 - C8) of a virtual object. In this early stage of research, we focus on the trade-off in rendering the size and location of a visual object as they are important parameters that largely influence the design of RetroShape applications. In particular, we were interested in

how tightly the size and location of the visual and tactile stimuli need to be matched. It is not always possible to precisely match the size and location of tactile stimulus with visual objects shown on screen, especially when the object is small. For example, sharp objects (e.g. an arrowhead) will not feel real if rendered using a 10 mm taxel. Studying the size gives us insights into the smallest object a typical high or low resolution taxel display can render. Studying how much the two stimuli need to be collocated allows us to understand how precise the location of an object can be haptically rendered under a certain taxel resolution.

STIMULI PILOT STUDY

Prior to Study 1, we conducted a pilot study to find the smallest taxel size that does not cause discomfort to users. We tested ten round-shaped taxels, ranging from 1mm to 10 mm in diameter on five participants. We used approximate 2 N force to generate the stimuli. The magnitude of the force was equivalent to a finger poke on the wrist. Results show only the 1mm taxel was remarked as uncomfortable. We thus chose to use 2 mm as the smallest taxel in our studies.

STUDY 1: ACCEPTANCE RANGE OF SIZE

This study’s goal is to determine the size range of a visual object that a taxel can realistically simulate. Participants were asked to discriminate the size difference between visual and tactile stimuli. We tested taxels of size 2, 6, and 10mm to determine the influence of taxel size on the range. The results of the study will help developers balance the resolution of the taxel display while maintaining a realistic user experience.

Participants

Eighteen paid participants (six females) between the age of 21 and 30 participated in this study. All of them are right-handed.

Apparatus

A single taxel was actuated above the user’s arm using a drawing robot (Figure 2a) from mDrawBot [30]. The robotic arm has a moving resolution of 0.1mm to allow precise control over the location of the taxel. It was mounted on a tilted standing desk, where participants placed their arm. The robotic arm held a 3D printed taxel. A servo motor actuated the taxel to the user’s wrist (Figure 2c) with a pressure of approximately 2-3 N (measured using a pressure sensor), enough to be felt by the users [42]. All the taxels were 3D printed in a round shape. We chose round instead of square to avoid influence on perception due to the change of the taxel orientation, a side effect that occurs when moving the robotic arm.

A Nexus 4 smartphone was mounted above the taxel to provide visual feedback (Figure 2b). The visual stimuli were rendered inside a 40×40 mm mock-up smartwatch screen (an average size between 38mm and 42mm Apple Watches). To ensure that visual and tactile stimuli appeared in the same location, we developed a tracking system by attaching a second phone to the back of the Nexus 4, with the touchscreen facing downwards, constantly in contact with an active stylus tip located right above the taxel. This way a touch point was registered where the taxel was located, which was used to determine the location

of the visual stimulus on the top screen. The phone and the robotic arm were calibrated before the start of the experiment. The tactile stimuli were randomized in each trial with a minimum distance of 15mm between two consecutive trials. Both stimuli were removed upon the end of a trial.

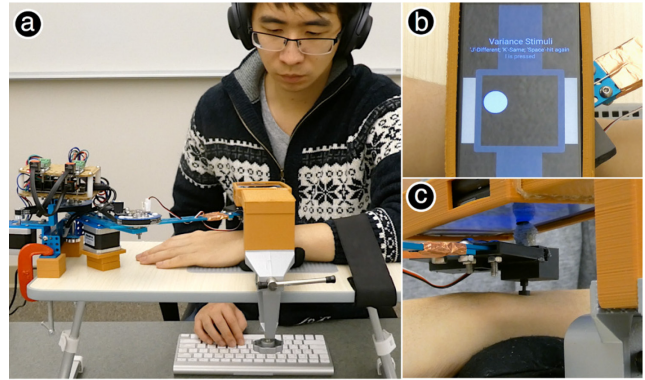


Figure 2. The apparatus of STUDY 1, which is composed by an robotic arm and two Nexus smartphones.

Design

The experiment consisted of a number of blocks, and each block consisted of two trials, one with the reference stimuli (S) and the other with the test probes ($S \pm \Delta S$). In the reference, the size of the visual and tactile stimuli matched, where the size S is the size of the visual stimuli, and ΔS is the difference between the reference and test size. The value of ΔS was determined adaptively, as described below. For each test trial, participants indicated whether the size of the visual and tactile stimuli matched. Responses were recorded and used to determine the value of ΔS in the next block. With the reference stimuli, participants were asked to specify, in a probe, their agreement on whether a given tactile probe was matched by objects of difference sizes shown on the screen. Their responses were influenced by visual clues from the reference trial, but this reflects a realistic setting where users already know the size of the taxel.

This design slightly modifies the standard approach of measuring just-noticeable difference (JND), where the reference stimuli is not provided to participants. We opted for the current design because the standard JND approach does not work in this situation as estimating a JND relies on the sense of discriminating the contact size based on a given tactile stimulus. This sensation can be developed through the use of RetroShape but untrained in our participants as the wrist is not a common place to receive this type of tactile stimuli. As a result, a forced-choice study would have resulted in less useful results for building RetroShape.

The acceptance boundaries for upper and lower bounds of the reference were found using a one-up-one-down adaptive staircase method [17]. The reference R were set to be 2mm, 6mm, and 10mm. The step size ΔS was initially set to a random number between 0 and $2R$. To mitigate the bias introduced by the initial start position, we conducted two staircase runs for each taxel size, with one starting from above R and the other

one below R . After the experiment started, ΔS was set to 15%. A negative response (e.g. the two stimulus did not match) brought the size of the visual stimulus closer to the reference by step ΔS , and vice versa. Reversals were detected after participants changed their opinion from positive to negative or vice versa. After the first five reversals, ΔS was set to 10%, and after the second five reversals, ΔS was set to 5%. A staircase run was terminated after 5 reversals with $\Delta S = 5\%$. The experiment finished after six staircase runs were completed (2 start positions \times 3 taxel sizes). The order of the staircase runs were counter balanced between participants.

Means of the last 5 staircase reversals were calculated for each participant. The upper bound was calculated by averaging the reversals above the reference R , and the lower bound was calculated by averaging the reversals below the reference. The estimated acceptance boundaries were computed by averaging the upper and lower boundaries of all the participants. The estimated acceptance boundaries were analyzed using a one-way ANOVA. Violations to sphericity used Greenhouse-Geisser corrections to the degrees of freedom.

Procedure

Before the start of the study, participants were asked to sit in a comfortable position and rest the non-dominant arm on a standing desk. The widths of their wrists were measured to ensure the taxel did not lose contact with their wrist. Each staircase runs took about 5 to 10 minutes, and breaks were given to the participants between them. The taxels were changed during the break.

To prevent the noise and movement of the robotic arm from influencing their responses, participants wore noise cancelling headphones during the study. The movement of the robotic arm was also hidden from the participants. Participants' arm movements were restricted on the standing desk using a velcro strap. A computer keyboard was placed under the standing desk for participants to give responses using the other hand.

Results and Discussion

The upper and lower bounds of each taxel's accepted size range is shown in Table 1. The result suggests that a taxel can simulate an object that is bigger or smaller than the taxel's actual size without breaking the realistic feeling. For example, the 2 mm taxel can simulate an object as small as 1.3 mm or as large as 2.9 mm. Many adjacent taxels can be actuated to simulate a bigger object, but actuating fewer taxels conserves battery. In addition, the lower bound field in Table 1 shows the smallest object a taxel can simulate. This is important when designing applications for low resolution taxel displays. For example, with 10 mm taxels, the smallest object that can be realistically simulated is 7.1 mm. As such, the display will not be able to realistically simulate an arrowhead stabbing the skin.

To examine whether the range of each acceptance boundary is affected by the size of taxel, we calculated a range/reference ratio for each tested taxel. The result showed no significant difference between them ($F_{1.4, 24.4} = 3.67, p =$

0.054), suggesting that the distance between the upper and lower boundaries (in percentage) do not change significantly with the change of taxel size. A comparison between all the percentages in the lower bounds ($F_{1.8, 29.9} = 1.3, p = 0.28$) and upper bounds ($F_{1.4, 23.78} = 2.6, p = 0.11$) yielded no significant difference. This suggests that the boundaries stay relatively unchanged across taxels of different sizes. Application designers can use the average number reported in Table 1 to estimate the boundaries for the taxels with different sizes. An interesting observation is that a 2 mm taxel display can render any object that is bigger than 2mm. For example, a 3 mm object can be simulated by using a 2 mm taxel (upper bound) or a 4 mm taxel (lower bound, which can be approximated using four 2 mm taxels. This may apply to the other taxel sizes as well but a careful study is needed to confirm this observation.

Taxel Diameter	2 mm	6 mm	10 mm
Lower Bound	1.3 mm; 65% (SE: 0.5 mm)	4.4 mm; 74% (SE: 1.4 mm)	7.1 mm; 71% (SE: 2mm)
Upper Bound	2.9 mm; 147% (SE: 1.8 mm)	8.9 mm; 142% (SE: 1.9 mm)	12.4 mm; 124% (SE: 1.5 mm)

Table 1. The lower bounds and upper bounds of taxels for each pin.

STUDY 2: DISCRIMINATION THRESHOLD OF LOCATION

In a low resolution taxel display, a visual object on screen and the corresponding taxel may not perfectly align. This study's goal is to determine the visual-tactile location discrimination threshold. Participants was asked to discriminate the location difference between visual and tactile stimuli. We again tested taxels of size 2, 6, and 10mm to determine the influence of taxel size on the location discrimination threshold. A standard JND approach was used in this study.

Participants

Eighteen paid participants (9 females) between the age of 22 and 30 participated in this study. All of them are right-handed.

Apparatus

The apparatus was the same as in Study 1.

Stimuli

The visual and tactile stimuli were the same as in Study 1. This time, location difference was varied rather than size.

Procedure and Experimental Design

Each user experiment consisted of a number of blocks, and each block consisted of two trials. One trial ran with the reference stimuli and one with the test probes. In the reference, the visual and tactile stimuli fired in the same location. In the test trial, they were set a certain distance apart (calculated as the distance between the centers of the two stimuli). The trials within a block were randomly ordered, and participants had to indicate which one is the test probe. Responses were used to determine the value of a step size ΔD in the next block. The stimuli locations of both trials were randomized.

The discrimination threshold of distance was found using a one-up-two-down adaptive staircase method [23]. The step size

ΔD was initially set to a random number between 5% -15 % of the size of the taxel. The delta was increased by ΔD after each incorrect response, and decreased by ΔD after two consecutive correct responses. After the first five reversals, ΔD was set to 10%, and after the second five reversals, ΔD was set to 5%. A staircase run was terminated after 5 reversals with $\Delta D = 5\%$. The order of the taxel size were counter balanced between participants. The participants were not given feedback about the correctness of their responses.

The average from the last 5 reversals were calculated for each participant. The estimated discrimination threshold of location for each taxel size was computed by averaging the means for each corresponding taxel. The estimated thresholds were analyzed using a one-way ANOVA. Violations to sphericity used Greenhouse-Geisser corrections to the degrees of freedom. Post-hoc tests used Bonneferoni corrections for multiple comparisons.

Results and Discussion

The primary finding is that taxel displays are able to simulate a realistic experience within a large location difference threshold (see Table 2). This suggests that even when visual and tactile stimuli are unaligned, they are still perceived as collocated as long as the distance between them is kept within the suggested thresholds.

Taxel Diameter	2 mm	6 mm	10 mm
Distance Threshold (between borders)	16.2 mm; 810% (SE: 0.71 mm)	11.8 mm; 197% (SE: 0.24 mm)	4.5 mm; 45% (SE: 0.11 mm)

Table 2. The distance thresholds for each pin.

We compared the three threshold/reference ratios. The ANOVA yielded a significant effect of taxel size ($F_{1,1, 20,5} = 124.9, p < 0.0005$). Post-hoc pairwise comparisons suggested that all the ratios are significantly different from each other (all $p < 0.0005$). This finding suggests that the location difference becomes easier to perceive with the increase of taxel size. Surprisingly, even with the lowest threshold (10 mm taxel), there is no overlap between the visual and tactile stimuli in physical location. We conclude that visual feedback dominates users' perception on location. As such, even a low resolution taxel display like the one we tested with 10mm taxels can realistically render the location of a visual object.

PROTOTYPE DESIGN, AUTHORING, AND TESTING

Encouraged by the results of Study 1 and Study 2, we created a proof-of-concept prototype called RetroShape (Figure 3). We then developed an authoring environment for developers to add taxel-based interaction to games and videos. We made our own demos using a set of taxel actuation patterns (primitives) we determined to be effective. Finally, RetroShape is tested in a user evaluation and the results analyzed.

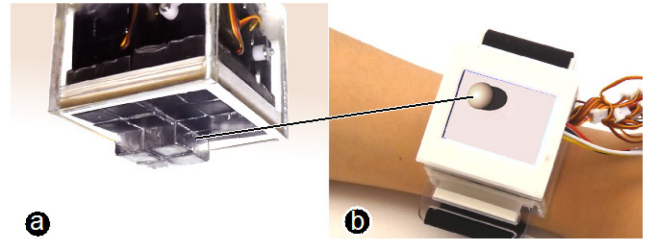


Figure 3. The RetroShape prototype, which is composed by (a) sixteen servo motors and taxels and (b) a 2" display on the front face.

RetroShape Prototype Design

RetroShape is composed of a 4×4 linearly actuated pin array. The pins were 3D printed, and have a 10×10 mm footprint with no space between them. Each pin is connected to miniature servo motors, which can extend to 7 mm from their resting position. Each servo motor weights 1.7 g, and has a dimension of $14 \times 6.2 \times 18$ mm ($l \times w \times h$). Under the working voltage of 3.7v, each servo motor can exert a twisting force of 75g and rotate in a maximum speed of 1200° per second. The motors are controlled using an Adafruit 16-Channel 12-bit PWM/Servo Shield, which was connected to an Arduino Mega board, communicating to a MacBook Pro laptop. Software was written in Processing.

The shape display has a modular design. We created a number of small modules composed of a 2×2 pin array (Figure 4a). The taxels were printed in square to fit the shape of the module. Since the forearm is less sensitive to shape [48], our study results still apply to the square taxels. Within each module, we positioned four servo motors in a stack to ensure that they occupy a minimum horizontal space. This way we optimized the size of the watch face over the thickness. The shape display dimensions are $23 \times 23 \times 39$ mm, which can be used a base module to create larger shape displays. In our prototype, we used 4 of them, resulting a system of 46×46 mm wide and 39 mm high (Figure 4 b). The pin arrays were held together using an acrylic glass watchcase. The watchcase holds a 2" TFT watch display. The taxels are indented 2mm from the bottom of the prototype to create a space for the motors to move so the watch does not have to be worn tightly. Although the prototype is thicker than a normal smartwatch, it can be worn on the wrist comfortably.

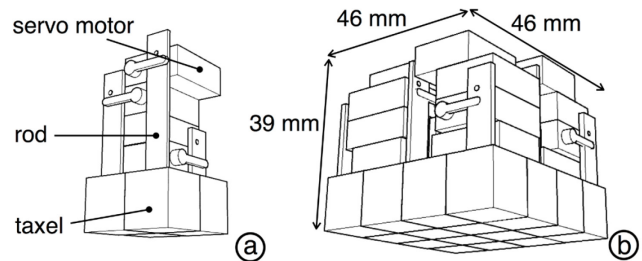


Figure 4. 3D models of (a) RetroShape unit and (b) a sixteen taxel array composed by four RetroShape units.

Authoring Environment

We created an application to help users create and edit shape-changing tactile feedback in videos and games. This makes adding tactile output more accessible to developers. With this tool, we created our RetroShape demo applications.

Creating tactile effect for videos

The application is composed of two views, a key frame editor view (Figure 5a) and a taxel view (Figure 5b). To start, a user specifies a taxel resolution (e.g. 4×4). The user then uses the key frame editor to scroll to the frame containing the start of a desired tactile event (e.g. the moment when a ball hits the ground). The user can drag-and-drop a pre-made tactile effect (e.g. explosion, Figure 5d) to the location on the screen, where the event takes place (Figure 5c). The duration of the tactile effect and the screen space involved (e.g. size of explosion) can also be changed. Users can create a tactile effect by manually adjusting the height of each pin in the key frame editor. Users first select a taxel and use a slider to specify the amount of taxel movement (Figure 5 b). The user then scrolls to the next key frame, and repeats the task. Between the key frames, the moving distance of each selected pin is interpolated using linear interpolation.

Pre-made effects can be created using greyscale animated GIFs, where the greyscale values in the GIF map to the height of the pin, with 0 (or black) indicating the rest position and 255 (or white) indicating the maximum height. In situations, where the resolution of the animated GIF is higher than the resolution of the taxel display, the software uses a pixelate algorithm (see Figure 5d, e) to partition the screen into a grid equivalent to the taxel layout (e.g. 4×4).

Creating tactile effect for games

Game developers can also use the animated GIF files to create tactile effects in their Unity games. Figure 6a-c demonstrates a simple Unity scene containing a ball bouncing against the ground. When the ball hits the ground, the Processing program loads a premade GIF that animates the taxels accordingly. We also created a simple API to allow the moving distance and speed of the pins to be dynamically controlled.

Demo Applications

We created a set of demo applications on our 4×4 resolution prototype to show case device capabilities and usage scenarios in various movies and video games. We define a set of taxel actuation patterns (primitives) to be modularly used in each of our demo applications.

Single collision. Actuated taxels can simulate a single collision. For example, in the bouncing ball scene, the taxel(s) can quickly tap the skin when the ball bounces away (capability C3, C6) (Figure 6a). The pin(s) can retrieve slowly to simulate the ball hitting an elastic surface (capability C7) (Figure 6b). A larger ball can be rendered by involving more adjacent pins (capability C1) (Figure 6c). We also used this capability in a Whack-A-Mole game to render the whack impact when the finger taps the screen (Figure 6d).

Multiple collisions. Taxels in the different locations can be engaged simultaneously to simulate multiple collisions, e.g. multiple balls bouncing against ground (capability C3, C4). The texture of a virtual object can also be rendered this way (capability C5). We use this capability to render the impact of gun fires in a first-person-shooter game (Figure 6f).

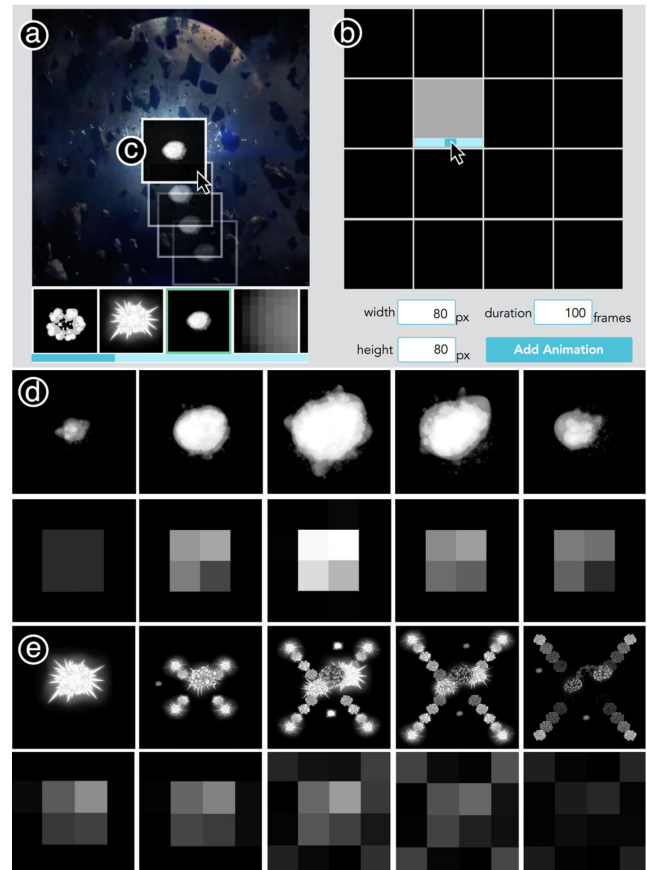


Figure 5. The authoring interface provides (a) a key frame editor view and (b) a taxel view. The designers can (c) drag-and-drop the (d) pre-made GIF files on the key frame and render the taxels.

Explosion wave (top view). This primitive simulates an explosion from a top-down viewing angle. The animation begins by engaging the taxels in the center, then quickly waves outwards in all directions (capability C1, C6, C8). We used this primitive in a Space Shooter video to render the exploding impact of hitting an asteroid (Figure 7a). Explosion wave can also be rendered in different shapes. In a Space Shooter game, we render the explosions in a circular shape when a meteoric stone is blasted (Figure 6e) and in a crossing shape when the player's jet is hit (capability C2) (Figure 5e).

Explosion wave (side view). This primitive simulates the explosion from a side view. Taxels wave horizontally by row towards the edges of the screen (capability C1, C6, C8). We used this primitive to render the impact of Chi wave blown out by Po when he becomes a Master of Chi (Figure 7b).

Flow. This primitive generates a moving pressure point on the skin (capability C3, C6) by triggering adjacent taxels in the object's moving path sequentially. Flow can be used to simulate a ball rolling on the skin. We also use it in a Space Shooter video to render an energy field moving from the right to the left side of the screen (Figure 7c).

Vortex. Vortex is rendered by moving the pressure point in a circular motion (capability C3, C6). We used this primitive to haptically render a space vortex in a Space Shooter video (Figure 7d).

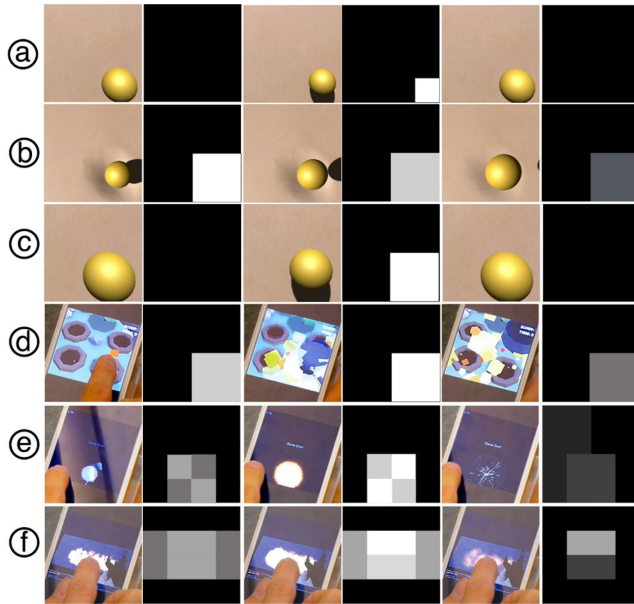


Figure 6. A simple unity game that loads and plays the GIF file (a) a small ball bounces against a hard ground or (b) elastic surface, (c) a big ball bounce against a hard ground (d) whack-a-mole, (e) space shooter, and (f) first person shooting.



Figure 7. The rows show abstract representations of primary events, including pressing, multiple collisions, explosion wave (top view), explosion wave (side view), flow, and vortex.

RetroShape User Evaluation Study

We conducted a user survey to assess user approval of the RetroShape concept. Our goals are two-fold: 1) investigate if the shape-changing tactile feedback is a valuable addition to vibrotactile feedback for providing realistic haptic

experience; and 2) investigate if the shape-changing tactile feedback can provide a user-preferred gaming and video experience.

Participants

We recruited eight paid participants (three females) between the age of 21 and 28 to participate in the study.

Experimental Design and Procedure

The study has two parts. In the first part, participants had the opportunity to compare a vibrotactile system to the RetroShape prototype through experiencing a ball bouncing demo on both systems. We rendered the size (small and big) and pressure (heavy and light) of the ball using either shape-changing tactile feedback or vibrotactile feedback. Size and pressure were chosen because they are important physical properties of an object. With RetroShape, a single taxel was used to simulate a small ball, and four taxels were used to simulate a bigger ball. The moving distance of the taxel(s) were set to 3.92 mm and 7 mm to simulate light and heavy pressure respectively. We implemented the vibrotactile system using the 10-mm ERM vibration motor, commonly used in haptics research [19, 24, 29]. A single vibrator was used to simulate the small ball, and four vibrators were used to simulate the big ball. The vibrators vibrated at 100 Hz and 170 Hz to simulate the light (0.75g) and heavy (1.25g) ball respectively. Our pilots suggested that it is a good mechanism to use the magnitude of vibrational amplitude and frequency to simulate the impact of a light/heavy ball bouncing against the wrist.

During the study, the order of Technique (RetroShape and vibrotactile) was counterbalanced, and the combinations of size and weight were randomized. Participants could try a condition as many times as they wanted. They were asked to rate the level of realism, size and weight can be rendered using the two techniques upon completing the first part of the study. The second part of the study measured user enjoyment of RetroShape in comparison to a tactile-free smartwatch. Participants had the opportunity to experience our demo applications (shown in Figure 6 and Figure 7) using RetroShape. For comparison, they then used the applications without the shape-changing tactile feedback. Similar to the first part, the order of Technique was counterbalanced. Upon completing this part, participants completed a questionnaire asking for ratings on enjoyment of their video and gaming experiences with and without RestroShape. All the ratings were from 1 to 5 using a continuous numeric scale with 1 least realistic/enjoyable and 5 most realistic/enjoyable. Decimal ratings like 3.8 were permitted. The entire experiment took around 20 minutes.

Apparatus

A modified RetroShape prototype was used and compared to a vibrotactile feedback device for user comparison. The RetroShape's TFT display was replaced using an iPhone 5 to capture input to the video games. The vibrotactile device had four vibrators (Figure 8). We followed the design recommendation suggested in [18], placing the vibrator tips

15mm apart from each other to allow distinguishable vibrations to be rendered by each vibrator. A damping sponge was placed between the case and vibrators to isolate the vibration.

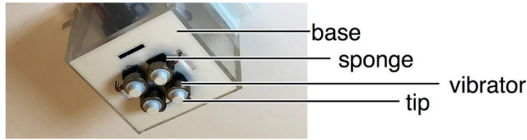


Figure 8. The vibrotactile array for the vibration condition.

Result and Discussion

The subjective ratings on realism and technique enjoyment were analyzed using a t-test.

Realism. Overall, the shape-changing tactile feedback received a significant higher score in realism than the vibrotactile feedback for rendering size ($p(7) = 3.6, p < 0.01$) and pressure ($p(7) = 3.4, p < 0.05$) (Figure 9). With respect to the object size, all the participants rated the shape-changing tactile feedback above 4. Participants reported that the difference in size were quite noticeable as *“the bigger ball felt much flatter on the wrist”* (P3, P8). On the other hand, participants could not intuitively associate the size with the vibrotactile feedback. A participant commented that *“the vibrotactile feedback created a blurry vibrational region that could hardly match the size of the ball”* (P5). Regarding the object pressure, the shape-changing tactile feedback was also rated higher. A participant commented that *“it is so cool and I felt the ball was actually sinking into the skin”* (P2). In contrast, most participants rated the vibrotactile feedback below 3 as *“weight has nothing to do with vibration”* (P3).

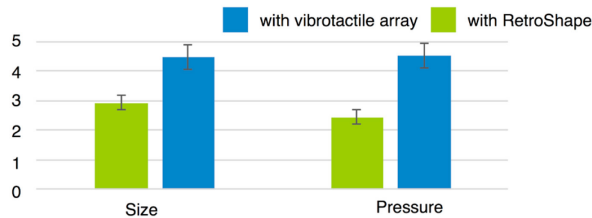


Figure 9. Realism scores of size and pressure factors. Error bars show standard error in all figures.

Enjoyment. Participants rated the shape-changing tactile display higher than no tactile feedback for the Whack-A-Mole (4.23, SD: 0.23; 2.70, SD: 0.26) ($p(7) = -4.318, p < 0.05$) and first-person shooting games (4.3, SD: 0.17; 3.28, SD: 0.33) ($p(7) = -4.023, p < 0.05$). They found it an enjoyable experience when they felt the exploding impact. Participants also liked Whack-A-Mole, and they all rated it at least 4. A participant commented that *“Wow! I felt like my finger penetrated the watch and touched my wrist”* (P8). An important finding is that participants suggested *“it would be nice to have both shape-changing and vibrotactile feedback”* (P1, P6) to render the impact of explosion. This confirms that the two tactile feedbacks can complete each other in situations where a high level of realism is required.

Surprisingly, the shape-changing tactile feedback (3.45, SD: 0.27) did not lead to a more enjoyable experience for the Space Shooter game (no tactile: 3.43, SD: 0.26) ($p(7) = -0.94, p = 0.93$). This is mainly because the crossing-shape exploding effect (Figure 5e) was not well received by the participants. A participant commented that *“The visual and haptic feedback do not matched very well”* (P3). This is a useful finding as it shows that mismatch between the visual and haptic feedback can largely mitigate user experience. In this case, a possible reason for the mismatch is that the resolution of the taxel display was too low to render the fine-grained details in the exploding scene.

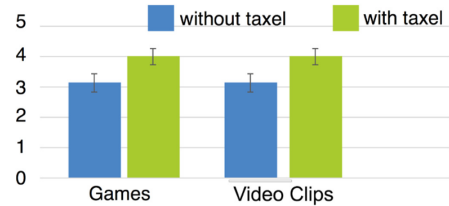


Figure 10. Enjoyment scores of the games and videos.

Regarding the video clips, participants rated the viewing experience significantly more enjoyable with the shape-changing tactile feedback than without any haptic feedback (all $p < 0.01$) (Figure 10). A participant commented that *“the tactile effect definitely provided a more immersive viewing experience”* (P3). Another participant said that *“this is unbelievable! I start seeing myself watching movies on my watch”* (P7). Another excited participant told us *“I want this watch”* (P6).

LIMITATION AND FUTURE WORK

In this section, we discuss the lessons and insights we learned from our experience. We also present limitations of our current approach and directions for future research.

Study: In an early stage of this research, we decided to conduct a fundamental study describing size and location thresholds for taxels of different sizes. These factors have an effect when simulating a visual object. While the knowledge we earned is limited to the binary signal of a single taxel, we were able to apply the information when designing the three ball bouncing/rolling apps and the whack-a-mole game. Future research will extend the studies to multiple taxels. Additionally, our preliminary user evaluation only suggests the comparison of our prototype and vibration in simulating size and weight. A more general study comparing the two feedback is needed.

Human perception: Our wrist is not sensitive to fine-grained shape change. This provides opportunities for developers to create immersive tactile effects using a low resolution taxel display. However, high resolution taxel displays are still preferred. Our initial user feedback suggests that in situations where a 4×4 taxel display was unable to render sufficient haptic details (e.g. exploding effect), user experience was largely impacted. Useful future research involves the enabling technology for higher resolution taxel displays.

The findings of human perception research can guide the design of software and hardware for higher resolution taxel displays. For example, investigating how well people can haptically perceive 2D or 2.5D shapes can help develop new algorithms to optimize taxel usage when rendering complex shapes. Further, studying the maximum number of haptic objects users can perceive simultaneously can be used to optimize the rendering algorithms, saving computing power and battery life. Discrimination threshold for textures can be another interesting topic for future research. Results in this class of research can guide the design and development of finer resolution taxel displays.

Tactile rendering: Aside from the taxel resolution, many aspects of the hardware can be improved. For example, adding vibrotactile feedback to the shape-changing display may increase realism. Skin-drag feedback is another user-experience enhancement for new haptic scenarios (e.g. simulating a zombie scratches the wrist). One way to simulate the skin-drag feedback would be to actuate the taxels in the horizontal plane. Future research will also integrate new tactile channels, such as airflow and temperature, to provide more immersive haptic feedback for video and gaming experience on smartwatches.

An obvious limitation of RetroShape is that the taxels can only be actuated along the normal of the screen. In videos, visual scenes need to be filmed in a top-down view to match the direction of the taxel display's feedback. Scenes filmed at a tilted angle are quite common. We do not know if the illusion will break when the orientation of the visual and haptic stimuli do not match. In the future, we will investigate the impact of mismatching the orientation of the two stimuli.

Implementation and form factor: Our current implementation is bulky. We will investigate alternative actuation mechanisms to minimize the thickness of the device. Ultrasonic motors are a good option because of the smaller size. A challenge, however, is to balance the size of the motor and the torque it provides. Additionally, our current implementation does not have an encoder to track taxel movement. RetroShape's taxel movement works fine in this initial exploration but future designs should consider using an encoder to more precisely control the movement of the taxels.

Evaluation: To expand the depth of our study's results, we will measure user perception in a less controlled environment. This better reflects how smartwatches are used in real-world situations. Standing, walking, or lying in a bed could lead to differences in study results. The pragmatic use of RetroShape warrants a careful investigation of its interaction in the wild.

Battery life: battery life is an important concern for wearable shape-changing tactile displays. Our current implementation uses an external power supply. We expect this issue to be mitigated with improvements in battery technology.

CONCLUSION

We propose a deformable tactile display on the back of a smartwatch to enrich gaming and video experience. We discussed the design space of this new tactile feedback and potential influence of the resolution of the taxel display on user's illusion of the presence of virtual objects. Through two controlled experiments, we determined how different taxel resolution effects user perception for different sizes and locations of virtual objects. In the first study, we investigated how tightly the size of the visual and tactile stimuli need to be matched. Our result showed that on average a taxel can render virtual objects between 70% and 138% of its own size without shattering the illusion. In the second study, we investigated how tightly the location of the visual and tactile stimuli need to be matched. The result showed that the two stimuli can be separated between 4.5mm to 16.2mm for the tested taxels without breaking the illusion. These results can provide useful insights for designers to create the shape-changing tactile feedback on smartwatches. Finally, we created a proof-of-concept prototype to demonstrate technical feasibility. The device is composed of a 4x4 taxels actuated using micro servo motors on the back of a 2" TFT display. We developed a set of games and videos on the device and evaluated them in a preliminary user study. The result showed that that participants welcome the proposed haptic feedback as a useful addition to the existing smartwatch output.

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