# Jetto: Using Lateral Force Feedback for Smartwatch Interactions

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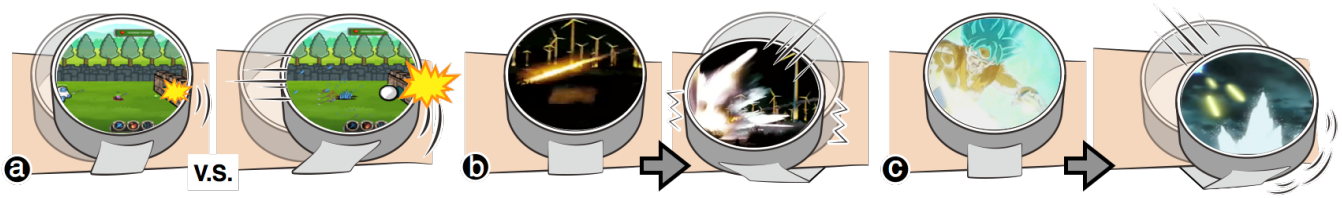


**Figure 1. Jetto creates lateral displacements on a smartwatch to simulate force impacts caused by a virtual object pushing or colliding into the edge of the watch screen, creating an illusion that the impact is created by a real object colliding inside the smartwatch. It simulates forces in different (a) magnitudes (e.g., weak vs strong); (b) directions; and (c) locations and durations.**

## ABSTRACT

Interacting with media and games is a challenging user experience on smartwatches due to their small screens. We propose using lateral force feedback to enhance these experiences. When virtual objects on the smartwatch display visually collide or push the edge of the screen, we add haptic feedback so that the user also feels the impact. This addition creates the illusion of a virtual object that is physically hitting or pushing the smartwatch, from within the device itself. Using this approach, we extend virtual space and scenes into a 2D physical space. To create realistic lateral force feedback, we first examined the minimum change in force magnitude that is detectable by users in different directions and weight levels, finding an average JND of 49% across all tested conditions, with no significant effect of weight and force direction. We then developed a proof-of-concept hardware prototype called Jetto and demonstrated its unique capabilities through a set of impact-enhanced videos and games. Our preliminary user evaluations indicated the concept was welcomed and is regarded as a worthwhile addition to smartwatch output and media experiences.

### Author Keywords

Wearable haptics; Haptic display; Smartwatch;

### ACM Classification Keywords

H.5.2. [Information interfaces and presentation]: User Interfaces – Haptic I/O



*CHI 2018, April 21–26, 2018, Montreal, QC, Canada*



ACM ISBN 978-1-4503-5620-6/18/04…$15.00

https://doi.org/10.1145/3173574.3174000

## INTRODUCTION

Smartwatches are beginning to shift from devices that provide quick and convenient access to information, to devices that also consume entertainment (e.g. videos and games) for brief periods of time, particularly in situations when users are on-the-go (e.g. using public transportation). While efforts have begun to accommodate these changes [23], the user experience is still quite limited due to the small-form factor and accordingly, the limited interaction space common to smartwatches today. Visual and auditory output on smartwatches have improved substantially, but opportunities for smartwatch-enabled haptics in the context of video and gaming applications, similar to those found in console gaming experiences, are yet to be fully explored and realized.

In this paper, we introduce a new type of haptic output on a smartwatch that simulates impacts caused by a push, collision or the inertia of a virtual object into the edge of the screen, through lateral force feedback. As the edge of the screen and the external watch case is typically aligned, this type of feedback creates the illusion of a virtual object that is physically hitting or pushing the smartwatch, from within the device itself (Figure 1). For example, in a movie scene that involves a crash, (e.g., a rolling car hits the edge of the screen), our technique generates a thrust force parallel to the screen in the same *direction* and *location* of the virtual force in the scene, causing a lateral displacement to the smartwatch, as if the smartwatch itself is being physically pushed by a real object. The user experiences the force impact shown in the scene by feeling a small displacement or shaking of the smartwatch body and the stretch of the watchband being pulled by the smartwatch. When combined with video and audio, this type of haptic feedback can be used to create a more immersive experience for smartwatch users, allowing the force of virtual impacts to be extended to the physical space. Our

approach physically pushes the watch body at the location of the event to simulate the direction, strength, duration, and dynamics of the force impact shown on the screen.

Developing this new type of haptic output for smartwatches, creates a number of scientific questions and challenges that need to be explored and overcome. In this early-stage research, we specifically focus on developing the fundamental knowledge around human perception issues for this type of feedback on a smartwatch. An important question we explore is the minimum change in force magnitude for a smartwatch that is detectable by users, as games and movies often have scenes or scenarios that show different levels of force impact (e.g., a castle that is hit by small or large rocks). We conducted a study to measure the discrimination thresholds (or just noticeable difference - JND) of force magnitude in two different force directions (e.g., vertical and horizontal) and three levels of weight of a smartwatch (e.g., 25g, 45g, and 65g). The result revealed an average JND of 49% across all the tested conditions. It also revealed that the JND was not affected by the direction of the lateral force and weight of the smartwatch.

Finally, we developed a hardware prototype called Jetto, a round-shaped smartwatch composed of a 3.5" TFT display and a pneumatic system, capable of generating lateral forces by emitting a jet of air (Figure 6). The orientation and location of the nozzle along the edge of the screen is controlled using two miniature motors. The current prototype is large and contains pneumatic components that could be hard to develop into a smartwatch form factor, but it serves as a means of investigating technical challenges, demonstrating interaction techniques, and provides preliminary feedback on our proposed lateral force feedback on a smartwatch.

The primary contributions of our work are: (1) the concept of creating lateral force feedback by physically pushing the watch body; (2) the results of a user study that investigated the influence of force direction and smartwatch weight on the discrimination threshold of force magnitude; (3) a set of applications that demonstrate the concept; (4) the results of a preliminary user evaluation on this new haptic feedback.

## RELATED WORK

We review the related literature in output on wearable devices, techniques to simulate force impact, and actuated mobile and wearable devices.

### Wearable Output

*Haptic output*. The limitations of size and form factor with wearables, severely impact their input and output capabilities. Overcoming these limitations has created several areas of research, particularly related to improving output using haptics. Haptics in wearable devices have appeared in a number of form factors, such as watches, gloves, shoes and belts [23, 32, 42, 46-48]. However, haptics in current wearables are not rendered in a rich manner. A majority of the existing work focuses on vibrotactile feedback [32, 42, 47]. For example, Pasquero et al. used the vibrotactile stimulation to deliver temporal notifications to smartwatch users [47]. Other work has used vibrotactile in a wearable form to provide feedback for driving [50, 51], navigation [64], notification [58], and motor skill training [36, 41, 44, 59, 62].

In smartwatches, vibrotactile feedback has largely been used for communicating low-bandwidth messages to the user [29-31, 34, 40]. For example, Pasquero et al. use vibrotactile stimulation to alert the wearer of important notifications [47]. Vibrator arrays have also been used to communicate with users using shapes [30, 40], strokes [29, 31], and alphanumeric patterns [33]. OmniVib [5] further extends these techniques to be used in the different locations of body. Skin Drag Display [25] uses a moving tactor to drag the user's skin to send messages to the user. On larger touchscreen devices, electro-vibration technology has also been used to simulate friction force, where moving a finger on a touchscreen provides a stretching feeling on the fingertip, simulating textures like bumps or gratings [9, 11, 53]. ThirdHand [35] is a wearable robotic arm that provides 5-DOF force feedback to enrich gaming experiences on mobile devices. GyroTab [7] is an ungrounded handheld device that uses the gyro effect to generate torque feedback. Shoogle [68] uses vibrotactile feedback to reveal the "inside content" when the mobile device is shaken.

*Visual output*. Aside from the haptic output techniques for wearables, a majority of research on output, particularly in the smartwatch domain, has focused on extending smart watch displays [39, 60]. For example, this concept is demonstrated by a Lenovo prototype smartwatch, where a second display is viewable by holding it up to the eye [15]. Similarly, Doppio uses a dual-screen approach in a smart watch form factor, with the secondary screen acting as a tangible screen [60]. AugmentedForearm [45] and Facet [39] also use a multi-display approach to extend the smartwatch screen and interaction space.

### Simulating Force Impact

In VR [65] and gaming applications (e.g. PS, Xbox game controller), vibrotactile feedback is a common cutaneous haptic stimulation used to simulate physical impact. However, many of the approaches based on vibration are ineffective on their own to realistically simulate the haptic feeling of physical impacts as vibrating the skin feels different than stretching or pressing with a certain amount of force [8, 28]. This is because vibration is sensed using Pacinian corpuscles (FA II), whereas stretching of the skin is sensed using the Ruffini corpuscles (SA II). As a result, it is well understood 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 experiences [27, 67]. Although, we

exclude vibrotactile in this work, it can still be a good addition in many scenarios.

Aside from vibrotactile feedback, electrical muscle stimulation (EMS) has been used to simulate force [37, 38]. For example, Impacto [38] simulates impact using a solenoid and adds impulse to the impact by thrusting the user's arm backwards using EMS.

Within the existing research space, RetroShape [23] is the most relevant to our work. It simulates physical impact using a shape changing display on the rear surface of a smartwatch. This technique, however, cannot simulate impacts in lateral directions. An alternative to this technique is shear force, which can be simulated on the fingertip using miniature motors [10, 17, 18, 54, 70]. This approach could be a better fit in smartwatch form factors, but it only covers part of the haptic feedback that our system can comprehensively offer. Our approach generates a more realistic lateral force to physically push the watch body at the location of the impact, allowing the user to feel a small displacement or shaking of the smartwatch body and the stretch of the watchband pulled by the smartwatch. This largely restores and mirrors physical impacts shown in virtual scenes on the screen.

### Actuated Mobile and Wearable Devices

Our work is also related to actuated interfaces, which have been widely studied in areas such as shape-changing devices [23, 43, 69]. For devices such as smartphones, self-actuation results in new forms of output [49] or dynamic affordances [57]. This is illustrated by Shape-Changing Mobiles [14, 20-22, 49], where the change in the shape of a device provides different forms of haptic feedback and notifications to a user.

Despite the well-explored areas of actuated interfaces in larger devices, self-actuated and shape-changing wrist wearables are still an emerging research area. The flexible phone concept by Lenovo [3], as well as SmartSound [2], are two examples of shape-changing mobile devices that bend around the wrist to create a smart-wristband. Similarly, PneUI [69] and LineFORM [43] are concept devices which are self-actuated and flexible, bending into the shape of a wristband. Cito [16] and RetroShape [23] are two examples of using self-actuation in smartwatches to provide haptic feedback in a variety of use cases.

We differentiate our research from these examples of actuated smartwatches and haptics by exploring lateral haptic-feedback, simulating impacts caused by a push, collision, or the inertia of a virtual object into the edge of the screen. This user feedback is important for improving both gaming and media experiences on smartwatches.

## FORCE FEEDBACK DESIGN SPACE

Simulating the force created by a virtual object pushing or colliding into the edge of a physical screen creates the illusion of an impact that is created by a real object colliding inside the smartwatch. This connects the digital and physical worlds, allowing a user to see and physically feel virtual impacts at the same time. In physics, force is an interaction that changes the motion of objects. It has a number of properties that can be controlled to realistically simulate the impact of a virtual event. In this section, we explore the design space of our lateral force feedback display for a smartwatch.

*C1: Location of force*. A force can be associated with an event happening at any location on the screen. We focus specifically on the edge of the screen, as it provides a strong illusion of an internal force being directly applied to the side of the watch case. Events can take place in either a single location or multiple locations. The force feedback should be generated at the location of the virtual event shown on the screen to give a realistic feeling and perception to the user.

*C2: Direction of force*. Aside from location, the direction of force also matters. The direction the force is physically applied on the smartwatch should be aligned with that of the visual effect on the screen.

*C3: Magnitude of force*. Force magnitude should be rendered at different levels to reflect the level of a virtual impact. This means that a stronger force should lead to a stronger sensation via the displacement or the dragging of the watchband on the wrist.

*C4: Duration of force*. A force should be haptically displayed for as long as the corresponding virtual event lasts. Short events, like the collision of two rigid objects (e.g., a rock hitting the smartwatch case) should be short in force duration, whereas simulating the collision of two soft balls should involve a longer force duration.

*C5: Impact size*. The physical size of a visual impact varies from scene to scene (e.g., the screen edge being hit by a big water cannon vs a smaller one). This can be reflected through the physical coverage area of the haptic system on the side of the smartwatch.

*C6: Force dynamics*. The location, direction, magnitude, duration, and size of a force may change temporally. For example, force magnitude needs to be reduced to reflect the reduction of water pressure when the tank of water supplying a cannon drains.

## HARDWARE DESIGN OPTIONS

In order to maximize the realism of the haptic experience, the hardware needs to generate realistic lateral force feedback by physically pushing the watch body. We briefly discuss the existing options in this section.

### Grounded Approaches

With these approaches, there is a physical attachment of the devices to the ground or body.

*Wheels*. Like [13], the watch body can be physically moved using wheels rolling on the wrist. The benefit of this approach is that the device can be self-contained. However,

the level of realism can be impacted, as the user feels the wheels rolling on their skin.

*Shear force display*. Shear force displays [8, 12, 17, 18, 54] are widely used in simulating object displacement. The technology is relatively well developed, but still faces issues around the level of realism it can render because shear force displays are not designed to physically move the watch body. In principle, the watch body can still be moved with a shear force display, but an opposite reaction force must be applied to the user (similar to wheels), thus potentially impacting the level of realism.

*Robotic arms*. Conventional haptic force displays commonly use a robotic arm to deliver force feedback. The technology has been proven effective in simulating a wide variety of force profiles for varying desktop [61] and wearable [35] applications. However, similar to the other body-grounded approaches (e.g., skin drag [25]), the experience may be impacted by the reaction force.

### Ungrounded and Other Approaches

With several of these approaches, there is no physical attachment of the devices to the ground or body.

*Linear Actuator.* Linear actuators (e.g., solenoid) [6, 24, 55] are also potential solutions to actuate the device to provide lateral force feedback. However, many of the existing devices provide insufficient force (e.g., 0.292N provided by Traxion [55]) for our study (e.g., 2N) or demo applications.

*Vibrotactile*. Vibrotactile feedback has been widely used in smartphones and smartwatches to simulate the impact of collision [68]. However, vibration alone is insufficient in applications requiring a realistic feeling of force to simulate physical impact which might include device displacement [23, 27, 67].

*Electrical Muscle Stimulation (EMS)*. EMS is widely used to achieve stronger force feedback in a compact form factor [37, 38]. While it might be possible to simulate lateral force haptic feeling, it does not physically push the device.

*Pneumatics*. The primary benefit of pneumatics is the realism it can provide. The technology can generate realistic thrust forces by emitting a jet of air. However, the implementation can be challenging and even potentially impracticable as it often needs an air compressor. No commercially available, off-the-shelf technical solutions are suitable for small wearable devices.

Therefore, with current technology, pneumatic systems may not be the most practical option in wearable form factors, but no alternative techniques can both generate sufficient realistic lateral force and physically move the device, which is essential for this type of haptic feedback. In this early stage, we chose to explore this novel haptic feedback with high realism, and examine more practical implementation comparisons for future work. In our experiments, we used a stationary air compressor to ensure that our study results were valid and generalizable to future haptic devices (not necessarily a pneumatic system), and capable of generating the same strong lateral force. We built a self-contained prototype with a $CO_2$ cartridge to maintain consistency and to demonstrate technical feasibility.

When developing applications for this type of haptic feedback, designers need to control the magnitude of the lateral force. It is thus important to know the minimum change in force magnitude that users can detect. This knowledge provides important insights into the development of hardware and software applications.

## STUDY 1: DISCRIMINATION THRESHOLD OF FORCE MAGNITUDE

The minimum change in force magnitude that is detectable is called the discrimination threshold of force magnitude. Weber [66] observed that most thresholds are proportional to stimulus intensity and thus can be expressed as:

$$\frac{\Delta S}{S} = C$$

Where $S$ represents the stimulus intensity, $\Delta S$ is the difference threshold or just noticeable difference (JND), and $C$ is a constant, called the Weber fraction.

In the context of smartwatches, the discrimination threshold of force magnitude is affected by many factors, such as the direction of the force, the size, weight and materials of the smartwatch and wristband, or how tightly the smartwatch is worn on the wrist. Given the early nature of this research, we focused on two crucial factors – *force direction* and *smartwatch weight*. We were interested in knowing whether a certain change in force magnitude is applicable for forces of different directions. Given all possibilities, the horizontal and vertical directions may be the most interesting. This is because the user perception of force magnitude could be affected by the watch band, which is pulled either perpendicularly or parallel to the force directions. We were also interested in knowing whether the same amount of change is applicable for smartwatches with different weights.

### Apparatus

We implemented the study apparatus using a pneumatic system, consisting of a stationary air compressor (California Air Tools 2010ALFC) and valves (Figure 2a). We increased the capacity of the air compressor using an external 10-gallon tank (California Air Tools CAT-AUX10A) for a longer duration of use. Air pressure inside the tank was controlled in a range between 100 and 105 psi. The flow of air was controlled using a proportional valve (Festo MPYE-5-1/4-010-B) and a solenoid valve (SMC VX222AAB, orifice 4mm) connected to the inlet of the Festo valve, to solve known leakage problems of the Festo valve. The valves were controlled using a laptop computer through a data acquisition module (Measurement Computing USB-231 DAQ Device), whose output voltage could be adjusted to control output air pressure.

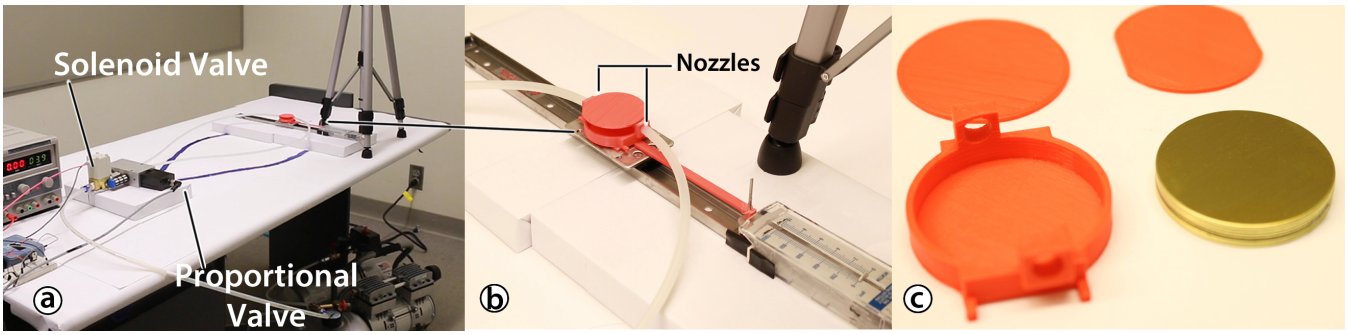


**Figure 2. Study 1 setup. (a) study apparatus; (b) 3D printed watch tethered to a spring scale with the watch mounted on a bearing ball carriage guided by a linear rail; (c) the watch was filled with brass discs for increased weight.**

The pneumatic system was then connected to a mock smartwatch, 3D printed in a round shape. The watch measured 42mm in diameter and 12mm in height, similar to the height of a Moto 360 (e.g., 11.5mm). It has two nozzles printed on the edge of the watch case, pointing outwards in opposite directions to randomize the force direction in the JND study, in which they were placed in either horizontal or vertical directions. Each nozzle was connected to an outlet of the proportional valve using a tube (Figure 2b). While the nozzle is turned on, it emits a strong jet of air to push the watch away from its resting position.

*Voltage-force mapping*

To precisely control output force on the watch, we conducted an experiment to identify the mapping between the nozzle's output force and required voltage from the DAQ. We mounted the watch on a bearing ball carriage guided by a linear rail (Figure 2b). The rail was well lubricated so, in theory, the friction between the rail and carriage could be ignored. As such, the weight of the watch had an ignorable effect on the result of our experiment. The magnitude of the output force was then measured using a 10N spring scale while the watch was pushed away (from its resting position) along the rail. We filmed the movement of the indicator of the scale using a high-speed camera. Force magnitude readings were recorded after the indicator stabilized (~150 ms).

The experimental setup can be made less complicated if a load cell was used to measure the force (e.g., no need to use a carriage, rail or video camera) (like [56]). However, our setup was still preferred, as it took into consideration the influence of the air tubes, which tethered the watch to the proportional valve. The resistance from the air tubes would not be considered if a load cell was used. Since the position of the tubes changed throughout the study, we marked their initial positions prior to the experiment, which we used as a reference to reposition the tubes before each trial, ensuring that the resistance from the tubes remained relatively constant. We also used this approach in our JND study.

The mapping experiment had a number of blocks, each consisting of three trials. In each trial, we applied a voltage via the DAQ and recorded the corresponding force magnitude. We took the averages of the three trials as our final readings. The experiment started from 0.02V and ended at 10V (high bound of the valve) with an increment of 0.02V, within which, half of the range (0V to 5V) was dedicated to the control of one outlet, and the remaining half (5V to 10 V) to the other outlet. This allowed us to retrieve the mapping for both outlets. The duration of force was set to 200ms, sufficient enough for the scale indicator to stabilize. The results, shown in Figure 3, highlight a steep curve occurring between 0 and 2N, after which the increase becomes significantly slower. We thus decided to use a range between 0 and 2N, and fit a polynomial curve to the data. The curve was used as a reference to identify a voltage value for a desired amount of output force.

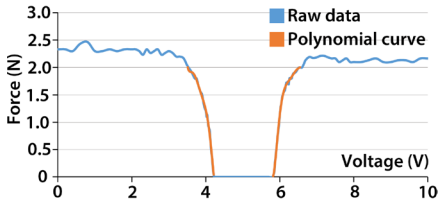


**Figure 3. Force magnitude shown by corresponding voltage.**

*Weight adjustment*

The 3D printed watch was 7.2g with the tubes. We filled the watch with brass discs (7.8g each) to increase its weight according to our requirements of the JND study (e.g., 25g, 45g, and 65g) (Figure 2c). Finer adjustments on the weight was made using modelling clay (e.g., Plasticine). We selected these three weights based on the weights of popular commercial smartwatches, ranging from 25g (e.g., Apple watch sport) to 67g (e.g., Samsung Gear). The shape of the watch remained the same for the entirety of the experiment and its conditions.

The study apparatus was carefully designed to ensure that the JNDs found in this study are independent of our hardware implementation.

### Participants

Twelve participants (3 females) between the age of 20 and 25 took part in this study. All of them were right-handed with a normal sense of touch.

### Stimuli

There were two force directions, horizontal and vertical. In the horizontal condition, half of the forces were randomly chosen to point west and the remaining half pointed east.

Similarly, in the vertical condition, half of the forces were randomly chosen to point north and the remaining half pointed south. Each force lasted about 150ms, sufficient enough for it to ramp up from 0 to the target values. We chose 150ms for its consistency with the length of stimuli in common JND studies (e.g., 100 – 200ms [63]),

**Figure 4. JND study setup**

Participants wore the watch on the wrist of the left hand in a sitting position, with the watch hand put on the table (Figure 4). We used a sport watchband for its popularity among smartwatch users (75% of users choose the sport watchband when purchasing an Apple watch [1]). The tightness of the watchband was controlled across all participants at around 8.5N (measured using a pressure sensor). This ensured the setup to be both comfortable and tight. Participants wore a down-filled jacket and gloves to prevent the feeling of air blowing on the skin. Finally, participants also wore noise-cancelling headphones (Bose QuietComfort 20) and a professional earmuff (3M Pro-Grade Earmuffs, 30dB NRR) to block the noise of the air compressor.

### Experimental Design and Procedure

The experiment employed a 2 × 3 within-subject factorial design. The independent variables were *Force Direction (Horizontal and Vertical)* and *Watch Weight (25g, 45g, and 65g)*. A JND was found for one of each of the *Force Direction* × *Watch Weight* combinations.

Each JND experiment consisted of a series of blocks, with each block composed of three trials, two with the reference force (S) and one with the test force ($S \pm \Delta S$). Trials were separated by 500ms intervals to ensure that participants' haptic memory were well kept [52]. For reference trials, the magnitude $S$ of the force was 1N, and for test trials, the force magnitude was $S \pm \Delta S$, where $\Delta S$ is a positive number representing the difference between the reference and test force. The value of $\Delta S$ was determined adaptively, as described below. The test force could thus be greater or smaller than the reference force. The three trials within a block were randomly ordered, and participants were asked to indicate which of the three trials had a different force magnitude by entering 1, 2, or 3 on a keyboard. Responses were recorded and used to determine the value of $\Delta S$ in the next block.

The discrimination threshold of haptic force magnitude was found using a one-up-two-down adaptive staircase method [26], which tracks a level of 70.7% correct responses. The step size ($\Delta S$) was initially set to 0.2N (10% of the maximum value), and increased by 0.2N after each incorrect response and decreased by 0.2N after two consecutive correct responses. After five reversals, $\Delta S$ was set to 0.1N. A staircase run was terminated after 10 reversals with $\Delta S$ = 0.1N. The experiment finished after six staircase runs were completed (2 force directions × 3 watch weights). The order of the staircase runs was counter-balanced between participants.

Participants performed practice trials before the actual experiment to ensure that they understood the task. The practice trials took no longer than five minutes. Each staircase run took between 15 to 20 minutes. Breaks were given to the participants in between.

### Result

The average from the last 10 reversals was calculated for each participant. The estimated discrimination threshold of haptic force magnitude for each of the six direction and weight combinations was computed by averaging the thresholds of participants. The estimated thresholds were analyzed using a repeated measures ANOVA.

The average thresholds and JNDs are shown in Table 1. ANOVA yielded no significant effect of *Force Direction* ($F_{1, 11} = 2.58$, $p = 0.14$) and *Watch Weight* ($F_{2, 22} = 0.80$, $p = 0.46$). There was also no significant effect of *Force Direction* × *Watch Weight* ($F_{2, 22} = 0.06$, $p = 0.94$). The average thresholds across all the conditions is 0.49N (JND = 49%). This result suggests that the change in force magnitude must be at least 49% higher or lower than the current force to enable people to perceive a difference. This JND can be used on smartwatches weighted within the tested range (e.g., 25g to 65g). There is also a trend indicating that the JNDs increased with the increase of the watch weight, but this must be confirmed in a future study with heavier weights. The JND was not significantly affected by the direction of the tested force, suggesting that the 49% JND is likely applicable for the directions not tested, as the influence from the watch band for the untested directions will become less. This will make application development relatively easier. Although further investigation with more directions is needed to confirm this finding, this initial result allowed us to guide the development of the demo videos and games.

| Watch Weight | 25g | 45g | 65g |
|---|---|---|---|
| Horizontal | 0.50N; 50% (s.e. = 0.05N) | 0.53N; 53% (s.e. = 0.05N) | 0.57N; 57% (s.e. = 0.05N) |
| Vertical | 0.41N; 41% (s.e. = 0.05N) | 0.46N; 46% (s.e. = 0.06N) | 0.49N; 49% (s.e. = 0.05N) |

**Table 1. Average thresholds and JNDs as a function of force direction and watch weight**

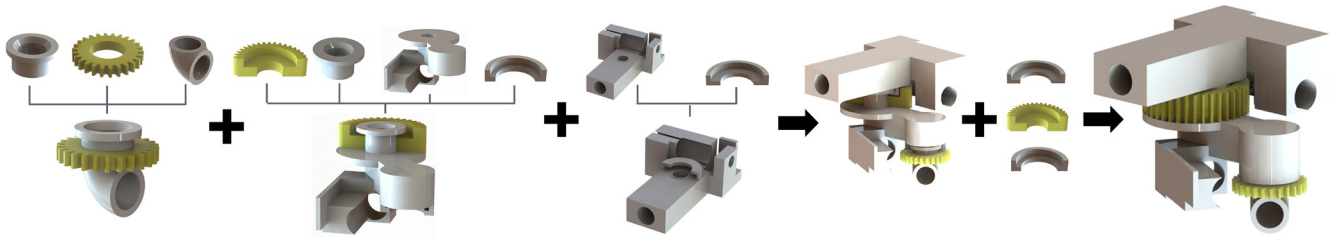

**Figure 5. A teardown of the pneumatic system used for lateral force feedback, consisting of custom 3D printed parts.**

We did not conduct a formal study to investigate the minimum force magnitude that is detectable by the users, as an initial study with five participants suggested that the threshold tended to be very small (e.g., ~0.01N). From a hardware perspective, we also believe 0.01N is too low for any practical use in video and game applications to warrant an investigation within the scope of our current work.

## PROTOTYPE DESIGN, AUTHORING, AND TESTING

Based on the results of our study, we created Jetto, a proof-of-concept prototype smartwatch (Figure 6) to demonstrate the novel interactions enabled by the lateral force feedback. We also implemented an authoring environment for developers to add lateral force feedback to videos and games. Lastly, we performed a user evaluation with Jetto and our results are discussed.

### Prototype Design

Jetto has two components: a frontend, composed of a 3.5" TFT display along with a mechanically controlled nozzle and a backend pneumatic system. The TFT display is mounted on a 3D printed watch case, measuring 58mm wide and 35mm high. Inside the watch, a 5mm nozzle is mounted on a rotary arm, actuated using a gear motor (Planetary Micro DC Motor, Gear Ratio 1:26, Firgelli Automations) with a worm gear system (Figure 6a). The rotary arm is 28mm long, allowing the nozzle to be moved along the edge of the watch case with a maximum speed of 135˚/s, fast enough for our applications. Inside the rotary arm, an air tunnel (also 5mm in diameter) was printed to connect the nozzle to the inlet. The nozzle can also rotate 360˚ to match the direction of a force, using a gear motor (Planetary Micro DC Motor, Gear Ratio 1:700, Firgelli Automations) and a worm gear with a maximum speed of 40˚/s. We applied grease to the connector of the nozzle and rotary arm to ensure a good seal. The entire mechanical system is composed of 12 components, including gears, connectors, rotary arm, motor holders, decoder holders, and inlet. Figure 5 demonstrates a teardown of the system structure. Finally, the motors are connected to a DRV8835 motor driver and an Arduino DUE microcontroller. The direction of the nozzle and the position of the rotary arm are monitored using an IR reflectance sensor (QRE1113, SparkFun Electronics). Custom C# software running on the laptop syncs the visual impact on the screen, and the position and direction of the nozzle.

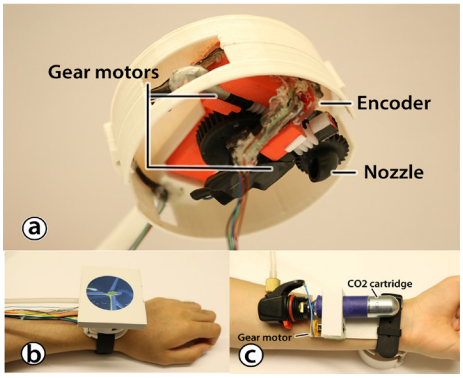


**Figure 6. Jetto prototype. (a) Jetto is composed of motors, an encoder and a nozzle. (b) front view; (c) the self-contained version with haptic output powered using a $CO_2$ cartridge.**

The haptic output was powered using a stationary air compressor. Alternatively, it can use also use a $CO_2$ cartridge for short-time usage, while staying in a wearable form factor (Figure 6c). Our implementation used an off-the-shelf CO2 Inflator with a built-in hand valve. The position of the valve is controlled using a gear motor (Pololu Metal Gearmotors), connected to a DRV8835 motor driver and an Arduino DUE board. A 20-gram cartridge can generate a maximum 1.8N force, and can be used at maximum force continuously for 5 seconds.

### Authoring Tools

To help users create and edit lateral force feedback in both games and videos, we designed a set of desktop authoring tools. The toolset is composed of an application for adding lateral force effects to videos and an API for integrating feedback effects into games. Using these tools, we created several demo applications for Jetto.

#### *Creating Force-Profiles*

To begin the creation of an effect, a user creates a force profile using our visual force editor by sketching. The interface contains a drawing panel, allowing the user to draw a curved line which the system then maps to the magnitude of lateral force. For example, the user can draw a bell shape to create a profile with fade-in and fade-out effects. Our tool translates the hand-drawn line into stair steps using the JND identified in our study, with a 70% step to accommodate the bulkier prototype. The force available to use is between 0N and 2N. The force profile is then

saved to a GIF that can be integrated into the video effects editor or the API for games.

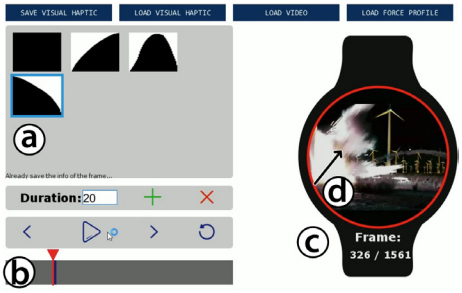


**Figure 7. Authoring tool. (a) List of force profiles; (b) timeline slider; (c) key frame editor; (d) force vector drawn by a user to define the direction and magnitude of the force in a frame.**

*Creating lateral force feedback for videos*

The watch-frame editor provides a visual means for users to add force-profiles to videos. To begin, a user loads a video into the application and uses the key frame editor to scroll to the frame where they would like to add a force-feedback event (e.g. when a fireball hits into the screen edge). Next, the user can select from a pre-made list of force profiles, made using our sketching tool, and assign it to the location of the event on the watch screen by simply clicking on that location. Dragging the mouse cursor from that location creates an arrow for the user to specify the direction and maximum force magnitude via the direction and length of the arrow respectively (Figure 7). Finally, the duration of the force can be specified by the number of key frames.

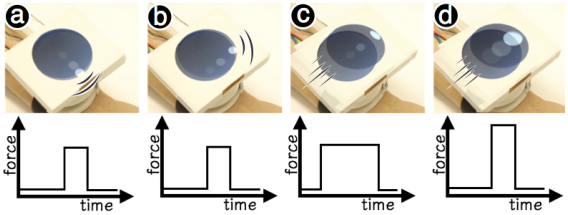


**Figure 8. A simple Unity screen showing a ball bouncing against the watch case (a) on the east side horizontally and (b) on the north-east side vertically. (c) a soft ball bouncing with a longer collision time; and (d) a heavier ball with stronger collision force. We also show force magnitude below.**

*Creating lateral force feedback for games*

For game developers using Unity, the previously created animated GIF files are used to add force feedback in games. Figure 8 demonstrates a simple Unity scene containing a ball bouncing against the edge of the smartwatch in different locations, from different directions, and with different magnitudes, and durations. A GIF with a force profile is loaded into a Unity scene, and when feedback is needed, the API internally loads the GIF and translates the animations into the appropriate force-feedback. Additionally, the API also allows for the customization of the direction and duration of the force.

## Demo Applications

To showcase Jetto and its capabilities, we created a number of demo applications and highlight various usage scenarios through three video games and movies. Each application demonstrates the use case of one or more of the force properties described earlier in our design space.

*Game*

*Air Hockey*. The lateral force feedback can simulate a single collision on different locations of the screen edge. For example, in the air hockey game (Figure 9a), when a puck hits the goal, force feedback can be felt (capability C1). The force can also be haptically rendered in the same angle of the puck hitting the goal (capability C2), thus different shots come with different effects.

*Tower Defense*. Force magnitude changes based on different weights of objects colliding into the virtual edge. We demonstrate this in our Tower Defense game (Figure 9b) where small stones lightly bounce off the castle against the virtual edge, while cannons cause a larger collision on the castle (capability C3) with a stronger force.

*Survival Shooter*. Depending on the type of object, a force can be continuous, such as a stream of water against a wall. We demonstrate this property with the Survival Shooter game, with a water gun continuously firing at the screen edge (capability C4). The force also fades away gradually after the character stops spraying water (capability C6). Switching to a laser gun results in a bigger sense of force and sudden fade (capability C3) (Figure 9c).

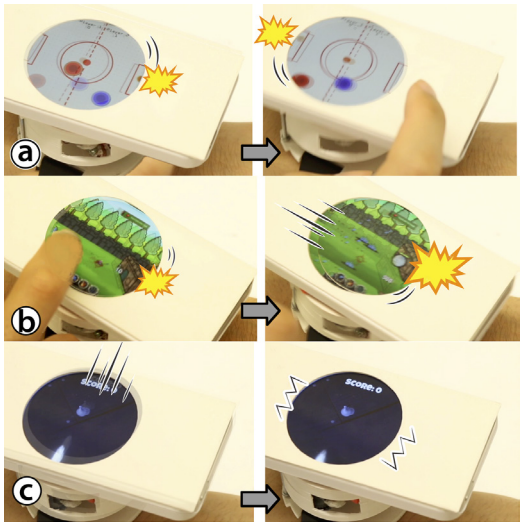


**Figure 9. Jetto games (a) Ice hockey; (b)Tower Defense; (c) Survival shooter.**

*Video*

*Dragon Ball*. We enhanced a video clip of Dragon Ball (Figure 10a) with lateral force feedback, where the force impact of Goku's fire balls hitting the ground or the mountain near the screen edge generates lateral force output (capability C1, C2). The duration and strength of the impact are rendered differently to reflect those of the visual and audio feedback (capability C3, C4).

*Mission Impossible*. With this example (Figure 10b), the user feels that the smartwatch is pushed towards south-west

when a missile hits the ground in the same direction. The smartwatch is pushed towards south when a wind turbine falls off the ground (capacity C1, C2).

*Car Racing*. This example gives the user a sense of centrifugal force when the car drifts (Figure 10c). The smartwatch is pushed either left or right at corners, to simulate the feeling as though the smartwatch is being pulled by inertia (capacity C1, C2, C6).

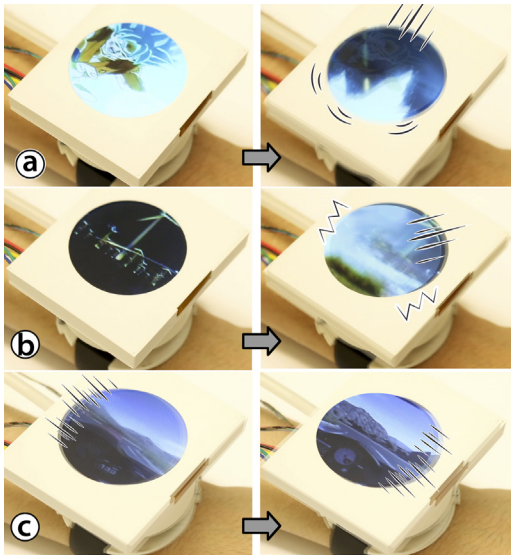


**Figure 10. Jetto videos. (a) Dragon ball; (b) Mission Impossible; and (c) Car racing.**

## Preliminary User Evaluation Study

We conducted a preliminary user evaluation using our prototype to assess user approval of the Jetto concept. Our goal was to investigate if the proposed lateral force feedback technique can provide a better gaming and video experience than no force feedback.

### *Participants*

We recruited eight participants (4 females) between the age of 20 and 28 to participate in the study. All participants had a normal sense of touch.

### *Experimental Design and Procedure*

The experiment was designed to measure the user enjoyment of Jetto in comparison to one without haptic feedback. Participants had the opportunity to experience the three games and videos (shown in Figure 9 & 10) using the Jetto prototype. For comparison, they also experienced the same applications *without* lateral force feedback. The conditions with and without haptic feedback were counter-balanced among participants. They could try the applications as many times as they wanted. After the study, participants completed a questionnaire asking for agreement ratings on enjoyment of their experience with and without the feedback. They were also asked to give agreement ratings on the level of realism for the force impacts rendered using Jetto. All ratings were from 1 to 7 using a continuous numeric scale, with 1 translating to a strongly disagree and 7 a strongly agree. Decimal ratings such as 5.8 were permitted. The entire experiment took about 20 minutes.

### *Apparatus*

The Jetto prototype was used in both conditions but feedback was disabled in the non-feedback condition. In the feedback condition, the feedback power was generated using the stationary air compressor. The TFT display was replaced with an iPhone 5 to capture touch input for the games. Participants wore the same noise-cancelling headphones and earmuffs as in Study 1. Sound effects from the videos and games were played through the headphones.

### *Result and Discussion*

The agreement ratings on realism and technique enjoyment were analyzed using one-way ANOVA and a t-test.

*Enjoyment*. Overall, participants' scores were slightly positive on the videos (Avg: 5.0; s.e. = 0.1) and games (Avg: 4.5; s.e. = 0.2) in the no-haptic condition. This is not surprising as the smartwatch still needs improvement for better game and video experiences. A participant reported *"I am not sure if I like to play Survival Shooter on a smartwatch as the screen is just too small to operate." (P8)* but the same participant also expressed *"but the force feedback (of Survival Shooter) is awesome!" (P8).* In contrast, participants found it a very enjoyable experience watching the videos (Avg: 6.2; s.e. = 0.04) and playing games (Avg: 6.3; s.e. = 0.04) with Jetto. While there is no significant difference between the scores on games and videos (both $p > 0.5$), the enjoyment scores with Jetto are significantly higher than the ones without Jetto (both $p < 0.001$). Positive comments on Jetto included *"cool and amazing" (P1), "impressive" (P3),* and *"I enjoy it!" (P3, P4, P5)*. With lateral force feedback, videos with fighting scenes instantly became more enjoyable to watch on a smartwatch. For example, a participant reported that "*I really enjoy feeling the watch being pushed continuously when Goku's kamehameha hits the enemy" (P3)*. Similarly, playing the games with Jetto was engaging. The most exciting comment we received was *"I was totally surprised when I felt the collision in the (Tower Defense) game. That was the moment that reminded me of the surprise and joy I had when I played my first video game and felt the vibration from the controller" (P7).*

*Realism.* Overall, the level of realism of Jetto was high for both games (Avg: 6; s.e. = 0.1) and videos (Avg: 6.2; s.e. = 0.1). In particular, Survival Shooter received an average score of 6.3 (s.e. = 0.1), Air Hockey received 6 (s.e. = 0.2), Tower Defense received 5.7 (s.e. = 0.3), Mission Impossible received 6.4 (s.e. = 0.1), Dragon Ball received 6 (s.e. = 0.2), and Car Racing received 6.1 (s.e. = 0.2). One-way ANOVA found no significant effect of applications ($F_{5,35} = 2.09$, $p = 0.09$). A participant commented on the Mission Impossible clip that "*the force matched the missile very well" (P1)*. Another participant said that *"it feels so real when the force appears with the collisions. This is what*

*I expected" (P7).* In general, participants agreed that their video experience was more engaging with Jetto than without it. As commented by a participant *"I felt so engaged, and the force feedback made me nervous when watching the movie clips" (P4)*. Participants also gave many inspired suggestions on how to improve the force effect. For example, a participant suggested that *"the strength of the force should be related to the speed of the puck (Air Hockey game)" (P1)*. Another participant stated that *"the direction of the force should also change when the car drifts (Car Racing video)" (P6)*. This suggests that integrating lateral force feedback into games and videos requires careful design efforts. Our authoring tool is an initial attempt for the technology to be accessible to designers. Additional work needs to be done to understand and overcome challenges for designers when making games and videos for Jetto and similar future devices.

## DISCUSSION AND LIMITATIONS

We discuss the limitations of our approach and suggest future research directions for exploring similar interactions.

*Implementation and Form Factor*: Our current implementation is thick, large, and relies on a round shape. Additionally, the use of compressed air and the plastic tubes for them limits its practical mobility. We will investigate alternative pneumatic mechanisms to minimize the thickness of the device techniques. Miniature $CO_2$ cartridges are a good option to overcome the size of the current prototype. However, there are complexities in balancing the size of the feedback mechanism and the force it provides. Another result from our implementation, and the reliance on larger air compressor tanks, is the loud noise it creates. Jetto's lateral force feedback system works sufficiently in our initial exploration but future designs should consider alternative techniques for pneumatics, as well as different watch shapes (e.g. square).

*JND Study*: As our research is early stage, we decided to conduct a fundamental study examining the factors of weight and force direction for lateral force feedback. These factors have an effect when simulating a physical impact. While the knowledge we learned is limited to horizontal and vertical force directions, we were able to apply the information learned when creating and designing the experiences for each of the three apps and games. Future research will extend our studies to multiple directions and locations simultaneously. Furthermore, our study focused on force directions parallel to the diameter of the smartwatch, but future research will investigate how the change in force direction at the same location may affect user perception. Lastly, a more general study comparing other feedback mechanisms is also needed, to better understand the tradeoffs and benefits of our approach.

*User Evaluation*: Jetto warrants a more careful evaluation in the field, in a less controlled environment. For example, understanding usability in scenarios such as walking, standing, or lying in a bed could identify issues not revealed in both our controlled study and evaluation. Moreover, we elicited preliminary user feedback using a non-haptic baseline. It will be our next step to compare different alternative practical solutions.

*Lateral Feedback Rendering*: Our experience suggests that having a lateral force feedback display with multiple and simultaneous directions is preferred (capability C5). Future research involves enabling multiple locations, simultaneous force effects, force size and more directions. Aside from the location and direction rendering our approach provides, one area we did not explore is alternative techniques that could provide more realistic force feedback. For example, providing force feedback in 3D would make first-person-based games a better experience. Combining the approach of Retroshape [23] with an actuated taxel would allow users to feel objects before, after and during collisions (e.g. feeling a ball rolling across the screen before colliding with a wall). Future research will combine feedback techniques, such as temperature, vibrotactile and skin-drag to provide more immersive haptic feedback for gaming and video experiences on smartwatches.

*Human Perception:* Our experience suggests that the wrist is not sensitive to fine-grained changes of force direction, which provides an opportunity for designers and developers to create immersive lateral force feedback effects using a force display limited in direction.

*Battery Life*: An important aspect of wearable devices with force feedback is battery life. In our current implementation, we rely on an external battery source, but we expect this issue to be resolved as battery technology and its efficiency steadily improves.

## CONCLUSION

Our work introduces a smartwatch that uses lateral force feedback to enrich gaming and video experiences. We discussed the design space of this type of force feedback and its influence on human perception. Through a controlled experiment (JND study), we first investigated the minimum change in force magnitude that can be detected by users, focusing on weight and force direction. Our results revealed the JND of force magnitudes is 49% across all tested conditions, with no significant effect of weight and force direction. These results can provide useful insights for designers creating and using lateral force feedback on smartwatches. To demonstrate technical feasibility, we created a proof-of-concept prototype, composed of a small 3.5" TFT display and a pneumatic system, capable of generating thrust forces by emitting a jet of air. The orientation and location of the nozzle along the edge of the screen is controlled using several miniature motors. Finally, to demonstrate the capabilities of Jetto, we developed a set of games and videos on the device and evaluated them in a preliminary user study. Our results showed that our proposed lateral force feedback is a meaningful addition to smartwatch media experiences and output techniques.

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