DeformWear: Deformation Input on Tiny Wearable Devices

MARTIN WEIGEL and JÜRGEN STEIMLE, Saarland University

Due to their small surfaces, wearable devices make existing techniques for touch input very challenging. This paper proposes deformation input on a tiny and soft surface as an input modality for wearable computing devices. We introduce *DeformWear*, tiny wearable devices that leverage single-point deformation input on various body locations. Despite the small input surface, DeformWear enables expressive and precise input using high-resolution pressure, shear, and pinch deformations. We present a first set of interaction techniques for tiny deformation-sensitive wearable devices. They enable fluid interaction in a large input space by combining multiple dimensions of deformation. We demonstrate their use in seven application examples, showing DeformWear as a standalone input device and as a companion device for smartwatches, head-mounted displays, or headphones. Results from a user study demonstrate that these tiny devices allow for precise and expressive interactions on many body locations, in standing and walking conditions.

CCS Concepts: • **Human-centered computing → Interaction devices**; **Interaction techniques**;

Additional Key Words and Phrases: Deformation input, soft user interface, small-surface input, wearable device

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1 INTRODUCTION

Wearable computing devices, such as smartwatches and head-mounted displays, have seen an impressive growth in commercial products and public interest. They can be used for a large variety of computing tasks, including remote communication, entertainment, navigation, health and fitness applications, or browsing the internet.

Current wearable devices trade off the size of their interactive surfaces for wearability, to be highly mobile and comfortable to wear on the body. Similar to prior handheld devices, they rely on touch as their primary input modality. However, as they are an order of magnitude smaller, touch input becomes very challenging: The small size of their interactive surfaces and the limited precision of touch input [32, 50] decrease the variety of actions a single touch contact can trigger on these devices. Therefore, current wearable devices must limit the set of possible actions or require additional navigation to select an action, such as scrolling.

These problems are a major limiting factor for further miniaturization of wearable devices. We envision future miniaturized devices could become as small as the head of a push pin and could be worn at a multitude of body locations for fast and unobtrusive input [26]. This tiny form factor requires novel techniques for interaction.

In order to enable expressive and precise input despite a tiny form factor, we suggest moving beyond touch-based input surfaces. We propose *deformation input on a soft surface* as an input modality for tiny wearable

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Author's addresses: M. Weigel and J. Steimle, Saarland University, Saarland Informatics Campus E 1 7, 66123 Saarbrücken, Germany.

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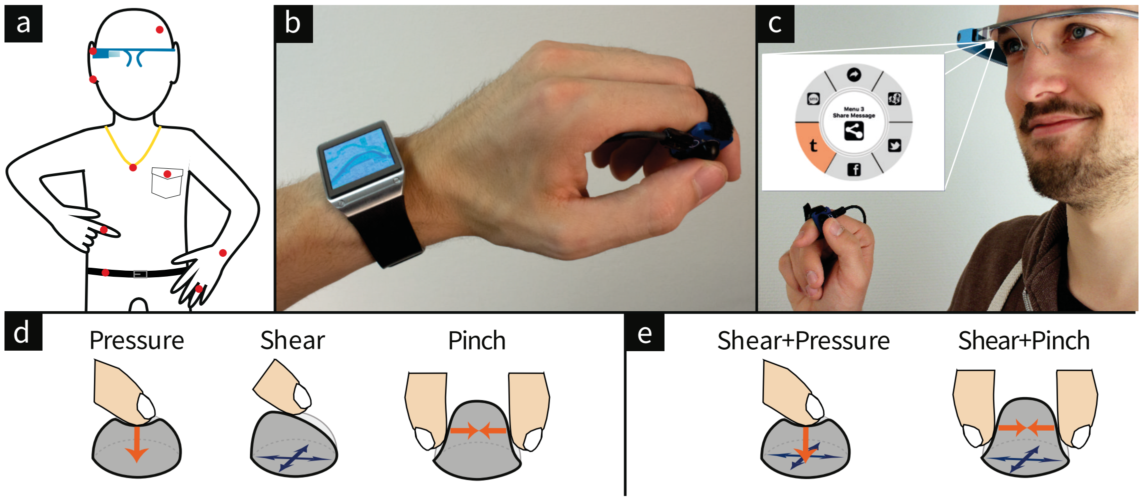

Fig. 1. (a) DeformWear enables expressive deformation-based input on various body locations: (b) One-handed input for smartwatches; (c) discreet input for head-mounted displays; (d) deformation primitives, and (e) their fluid combinations.

computing devices. Inspired by the softness of skin and clothing, it leverages the additional degrees of freedom for interaction offered by soft input surfaces. The user interacts at a single location by pressing, pinching, and shearing the deformable object (Figure 1).

Such deformation input is well-suited for tiny input surfaces, since it does not rely on position features and requires only minimal finger movement. Despite the tiny surface, interactions can be precise and expressive, because they leverage the precise motor capabilities of the fingertip and because they draw on three deformation primitives (pressure, pinch, shear). Each of them can be continuously manipulated and they can be combined in a single gesture. The deformation-input on these tiny devices requires no visual attention. Moreover, it allows for subtle and private input, which is barely noticeable to bystanders and can be beneficial for social acceptability in mobile scenarios [36]. This paper presents three primary contributions:

(1) We introduce DeformWear, a novel class of tiny and expressive wearable input devices that uses pressure, pinch, and shear deformations. Their tiny form factor supports a variety of different body locations. We describe the interaction space for tiny deformation-sensitive wearables, illustrate possible locations for DeformWear, and demonstrate the technical feasibility with three functional device prototypes: a ring, a bracelet, and a pendant (see Figure 2).
(2) We illustrate the capabilities of DeformWear by contributing a set of deformation-based interaction techniques for tiny wearable devices. The techniques enable fluid interaction in a large input space by combining multiple dimensions of deformation, mitigating input problems on existing wearable devices. For example, DeformWear allows for fluid, one-handed navigation on smartwatches, interaction in a large gesture space, and discreet menu selection. We demonstrate the interaction techniques in seven application examples, showing DeformWear as a standalone input device and as a companion device for smartwatches, head-mounted displays, or headphones.
(3) We report empirical findings on deformation-based input on tiny wearable devices from a controlled experiment with users. The findings detail the performance of three devices worn on different body locations (bracelet, pendant, and ring), both in standing and walking conditions. The results show that pressure, shear, and pinch deformations enable fast and precise input. The participants were able to

distinguish and hold up to six deformation levels in each direction. Furthermore, combined pressure and shear, as well as combined pinch and shear deformations, can be performed simultaneously, which allows for fluid and multi-dimensional input. The results also demonstrate large effects of one-handed vs. two-handed interaction in walking conditions, which has important implications for the choice of an appropriate body location and device form factor for DeformWear input. We conclude by providing design recommendations for wearable devices with multi-dimensional deformation input.

2 RELATED WORK

This work is informed by prior research on input techniques for wearable devices, interactions in vicinity of wearable devices, deformation input, and deformation sensors.

2.1 Input Techniques on Wearable Devices

Overcoming the limitations of the small input surface of wearables has been a long-standing topic for research. One stream of prior work leverages previously unused parts of wearable devices as an input surface. This includes touch-sensitive wristbands [31], bezels [28], and cords [39]. Others have increased the effective resolution of input by using a nano-stylus [57]. Another approach consists of modifying touch gestures to be more compatible with small displays, for instance through tapping gestures [29]. Beyond touch input, Xiao et al. presented pan, twist, and click input for smartwatches [58]. While these interaction techniques improve interaction with existing mobile devices, they do not scale to tiny devices. On the body, prior research proposed input on the small area of the finger [41], including touch-sensitive fingerpads [6], nails [18], and rings [7]. These devices were intended specifically for body location on the hand to provide fast input using touch.

Isometric joysticks enable force-sensitive shear input and can have a small form factor, similar to DeformWear. Selker et al. investigated isometric joysticks for pointing input on laptops [40]. Wobbrock et al. proposed an isometric joystick for two-dimensional gestures on mobile phones [56]. Their force input is limited to the two-dimensional shear input. DeformWear expands this input space by sensing continuous pressure and pinch input in combination with the two-dimensional shear input, increasing the expressivity of mobile computing.

Ni et al. presented a radical vision of disappearing mobile devices [26]. They used a reversed optical mouse sensor to capture input performed by moving a finger on the sensor. The work demonstrated the feasibility of discrete 2D gestures, e.g., marking gestures and unistroke text entry. Inspired by this work, we propose continuous deformation input instead of motion-based gestures, making use of multi-dimensional interactions for a larger and more expressive input space.

2.2 Interaction in the Vicinity of Wearable Devices

As an alternative to direct input on the device, prior research investigated in-air gestures that are performed in the vicinity of the wearable device [2, 5, 12, 34, 55]. These are not restricted by the size of the device. Another approach is interaction on clothing [19, 23, 33] or on skin [11, 13, 30, 53]. Such interactions increase the input space by extending it to surfaces that are commonly available on the body. In contrast, DeformWear is designed for expressive and precise input directly on small wearable devices.

2.3 Deformation Input

Various types of deformation input have been investigated from a human–computer interaction perspective. Prior research investigated a deformable computer mouse [46] and mouse pads that sense their deformations [20]. These devices increase the input space of pointing devices with additional pressure deformations that can act as hotkeys. On touch-screens, deformation input can increase the expressiveness by sensing pressure, thrust, twist, and pinch input [27, 38]. Similar deformation gestures are also supported on smartphone extensions [21, 52].

Interaction with DeformWear is based on these deformation primitives, i.e., pressure, shear, and pinch input, as well. DeformWear investigates and evaluates these primitives in the context of wearable computing, which requires different device form factors and novel interaction techniques.

Deformation input has also been investigated for 3D-shape manipulation [25] and digital relief modeling [10]. These interaction techniques use the input location together with the amount of pressure deformation to reshape digital objects. However, their location-based interactions are primarily intended for handheld input devices and are challenging to perform on wearable devices, due to their smaller input surfaces. Hence, DeformWear trades localized deformation input for high wearability.

Prior research on thin and flexible handheld devices presented paper-like input modalities, e.g. bending, rolling, and flexing [35, 44]. Karrer et al. proposed pinching and rolling of clothing [19]. These technologies enable deformation sensing on large loosely-attached or handheld surfaces. In contrast to these approaches, DeformWear uses a tiny and soft input surface as a wearable input device. This requires a different set of deformation primitives, due to the smaller form factor and the attachment to the body. Despite these differences, DeformWear could be integrated into clothing, e.g. it could be used as a cuff button. However, not relying on fabric allows for a wider variety of body locations and form factors, such as integrating the sensor in jewelry.

Deformation of large flexible displays enables 3D data exploration and novel artistic visualizations using free-form deformations [4, 44]. In contrast to these devices, DeformWear is an order of magnitude smaller and its surface is mostly occluded by the finger during interaction. Therefore, we opted for external output such as body-worn displays in proximity to DeformWear, head-mounted displays, and audio feedback.

DeformWear is in large part inspired by deformation input on soft surfaces like skin [30, 37, 54]. Skin has been used as an interactive surface for shear and pressure input [30, 37]. Recent work on conformal skin electronics demonstrates sensing squeeze input on skin [54], similar to the pinch input presented in this paper. DeformWear uses these three deformation primitives (pressure, shear, and pinch input) on a soft body-worn input surface. Expanding the interaction space of prior work, this paper investigates input techniques that combine multiple high-resolution deformation primitives to enable fluid, multi-dimensional interactions. Moreover, we extend the empirical understanding of wearable deformation input by evaluating DeformWear's deformation modalities on various body locations and during mobile scenarios such as walking.

2.4 Deformation Sensors

Many technologies have been proposed for deformation sensing, including resistive, magnetic, and optical sensing. Resistive sensing embeds conductive material inside a deformable object. For example, Vanderloock et al. filled soft objects with conductive material and measured the resistance across multiple electrodes [49]. Slyper et al. sense deformation of objects through contacts of conductive parts on their outsides [42]. FlexiBend is a shape-changing strip made from strain gauges that can be embedded into objects for deformation sensing [8]. DefSense embeds piezoresistive wires into flexible 3D prints [1]. Flexy demonstrates the rapid fabrication of custom-shaped flex sensors for interactive thin-film surfaces using conductive inkjet printing [48]. Based on magnetic sensing, Jamone et al. show deformation sensing in deformable silicone [16] and Jacobson et al. presented magnetic sensing in 3D prints [15].

In the robotics community, optical force-sensitive deformations are used for their fast response and high resolution. Kadowaki et al. measure the light distribution between infrared LEDs and photoresistors in a soft urethane foam [17]. Sugiura et al. measures the reflective IR light inside a deformable object [45], e.g. cushions and plush toys. Our DeformWear prototypes are based on an optical deformation sensing technique introduced by Tar et al. [47]. Its small form factor ($\oslash 10mm$) and robustness make it a suitable technology for wearable computing. However, future DeformWear devices could be based on other technologies, since our proposed interaction techniques are not limited to a concrete sensing approach.

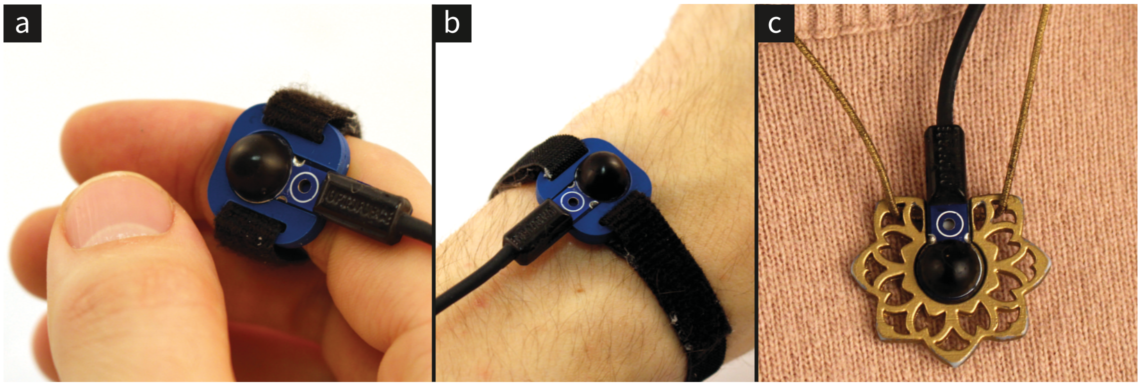

Fig. 2. Functional DeformWear prototypes: (a) ring, (b) bracelet, and (c) decorative pendant.

3 DEFORMWEAR CONCEPT

DeformWear proposes expressive deformation input on a tiny form factor. This opens up a novel and unexplored design space for wearable devices. In the following we provide detail on the rationale behind DeformWear's form factor, on body locations, and on the primitives of deformation input on tiny surfaces.

3.1 Form Factor and Size

DeformWear input devices are tiny wearables that have an input surface smaller than a fingertip. They offer a soft input surface that can be continuously deformed in different ways and with different strengths. The sensing principle behind DeformWear would allow for a completely flat input surface. However, we chose a slightly protruding sensor surface to provide tactile cues. The tactile feedback on the interacting fingertips can help to locate the input surface. Furthermore, the slightly angled contact points ease the deformation input and allow for a better grip. Due to the tiny input surface, DeformWear devices can be designed to be visually unobtrusive, which supports social acceptability. Furthermore, input can be discreet, since deformations do not require large movements or gestures.

3.2 Body Locations

The tiny form factor allows a DeformWear input device to be worn at many body locations for always-available interaction. Figure 1a shows various possible locations. The form factor is highly compatible with a large variety of existing body-worn objects, including jewelry (e.g., pendants, rings, earrings), accessories (e.g., buttons, bracelets), piercings, and existing wearable devices (e.g., smartwatches, head-mounted displays, in-ear headphones, fitness trackers).

From the large space of supported locations, we chose three input locations to be investigated in more detail. They were inspired by locations suggested in prior work on disappearing mobile devices [26] and body-worn wearables [41, 43]. These locations highlight important body areas and device form factors, and allow us to study different interaction styles, most notably one-handed vs. two-handed interaction:

3.2.1 Input on the Finger. The tiny surface of DeformWear allows for one- and two-handed input on the small surface of a finger, e.g. by integrating it into a ring (Figure 2a). A well-suited location is the middle segment of the dominant index finger, with the input surface facing towards the thumb. This location offers ergonomic access [14] and avoids interference with grasping. Compared to prior solutions for touch input on the finger [6, 7, 18], DeformWear input is not restricted by the size of the surface, nor does it require finger displacement.

3.2.2 Input on the Wrist. The wrist is a frequently used location for body-worn accessories (e.g., bracelets, cuff buttons) and wearable devices (e.g., smartwatches and fitness trackers). It is quick and easy to access using the fingers of the other hand. DeformWear input can be integrated into wrist-worn objects (Figure 2b) to enable fast and expressive interactions. For instance, integrated in a cuff button, it can enable direct-to-access and expressive interactions for head-mounted displays. Added on the strap of a smartwatch, it enables occlusion-free input.

3.2.3 Input on a Graspable Pendant. DeformWear can be integrated into jewelry and accessories that are loosely attached on the body. For instance, it can be integrated into the pendant of a necklace (Figure 2c). The location at the chest is quick to access, convenient to grasp, and a common location for jewelry for men and women. The loose attachment of the pendant allows the user to hold the input device using a comfortable posture. For example, the pendant can be grasped with one hand for one-handed thumb input. Alternatively, it can be held with one hand and interacted on using the fingers of the other hand. Other loosely attached graspables, e.g. pocket watches, can be used in similar ways.

3.3 Deformation Input

The deformation input of DeformWear offers a large, continuous input space. The fingers interact around a single device point, with little finger displacement, by exerting small forces. The forces create deformations on the soft input surface, which are measured by the device. The DeformWear device senses three deformation primitives simultaneously. All of them can be performed in one-handed or two-handed interactions (Figure 3).

Pressing Pressure deformations are created when the user presses on the DeformWear sensor using the thumb or another finger (Figure 3a). Our prototypes support continuous pressure forces from 0 to 5N. This fully covers the typical forces exerted by fingers.

Shearing Shear deformations are created through a tangential force that the thumb or finger exerts on the upper side of the sensor (Figure 3a). Shear offers a rich two-dimensional input channel. Shear deformations contain two parameters: the deformation force (0 N to 5 N) and the direction of the deformation (0–360°).

Pinching Pinch deformations are created by squeezing the DeformWear sensor with the thumb and a finger. This creates opposed compressive forces on the sides of the sensor (Figure 3b). Our prototypes measure continuous pinch forces up to 5 N.

The precision of three-dimensional deformation input allows for a high degree of expressiveness on a tiny input surface. Combinations of the three deformations primitives further create a rich multi-dimensional input space. Lastly, tactile feedback about the deformation force and its direction support the user, without requiring visual attention.

4 IMPLEMENTATION

This section describes the sensing principle and the implementation of three wearable prototypes.

4.1 Deformation Sensing

DeformWear uses optical deformation sensing. It measures deformations created by a three-dimensional force vector on the soft, elastic surface. An infrared LED in the middle of the sensor illuminates the inner structure of the hemisphere. The reflected amount of light is measured using four light-sensitive photodiodes. The intensity of the reflected light can be mapped to continuous deformation [47]. For instance, when the finger presses on the top of the sensor, the distance between diodes and surface decreases, resulting in a higher light intensity

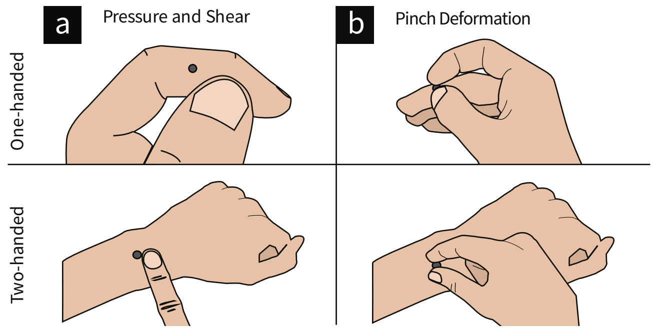

Fig. 3. DeformWear supports one-handed and two-handed input: (a) pressure and shear deformations; (b) pinch deformations.

(Figure 4a). During shear, the distance between diodes and surface changes asymmetrically, e.g., shearing to the left increases the distance for the left diode while it decreases the distance for the right diode (Figure 4b).

We implement this approach using a force-sensitive sensor that was developed for industrial robots (OptoForce OMD-10-SE-10N, see Figure 5). Our experiments showed that the sensor is also very capable of sensing deformations created by a human finger (Figure 4a–c). The sensor covers the typical force range of the hand (approximately 5N). The sensor has a high resolution (2.5 mN), and low energy consumption (10 mA). It has a small nonlinearity (2–5%), small crosstalk between diodes (5%), and small hysteresis (<2%). It sends the four diode's intensity values, filtered using a 15 Hz low-pass filter, via USB at 100 Hz. These properties enable precise and expressive deformation input for wearables.

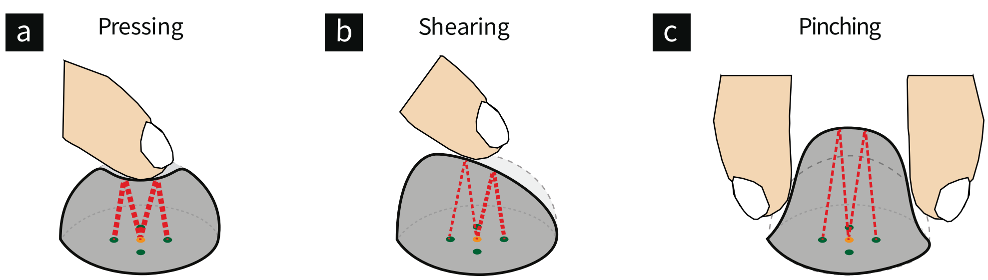

Fig. 4. Deformation sensing using four light diodes: (a) pressure deformation increases the amount of measured light on all diodes; (b) shear deformations change the amount of measured light asymmetrically; (c) pinch deformations decrease the amount of measured light on all diodes.

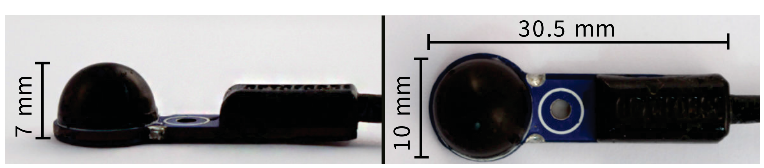

Fig. 5. Sensor used in our prototypes.

The sensor measures the pressure and slippage forces. These force measurements are directly used in DeformWear to detect the *pressure and shear* deformations. However, by default the sensor only captures 2.5-dimensional input: an opposite input to pressure is not supported. This would considerably limit the capabilities of such an input device for human–computer interaction.

We address this issue by contributing a sensing technique for capturing *pinching* input. Pinch deformations have not been previously studied on this class of sensors. By inspecting the sensor's raw values, we found that a pinch results in a unique sensor response. A pinch presses two opposite sides of the sensor towards the center; hence, the distance of all diodes to the surface increases (Figure 4c). The decrease in the diode reading created by a pinch deformation can be measured using the following equation:

$$D = \frac{\sum_{i=1}^{4} (\beta_i - S_i)}{4}$$

where S_i is the raw reading of diode i and β_i is its baseline value in the rest state when the sensor is not deformed.

In a technical evaluation, we studied the sensor's characteristics for pinch deformations. We built an evaluation setup to apply symmetrical forces on both sides of the sensor (Figure 6a). The forces were measured by two force-sensitive resistors (FSR 402). A 3D printed cone connects a 5 mm tip with the force-sensitive area on the FSR. Figure 6b shows the relation between pinch forces and the sensor response D using the formula above. The plot shows a continuous sensor response and a high dynamic range. A linear function showed a good fit to the sensor data ($r^2 = 0.935$) and is used as a continuous mapping function. However, it must be noted that very low pinch forces (<1 N) cannot be precisely captured. As such small forces generated a slight deformation of the sides of the sensors, the center of the hemisphere, where the diodes are measuring the signal, remained virtually undeformed. This could be improved in future implementations by a slight readjustment of LEDs and photodiodes, such that they directly capture the deformations of the sides of the hemisphere. Overall, the evaluation shows that continuous pinching input can be captured with a high resolution. Hence, the same sensor hardware can be used to capture three types of deformation and to enable full three-dimensional input.

4.2 Prototypes

We realized functional prototypes of three DeformWear devices: a bracelet, a ring, and a pendant (Figure 2). The prototypes feature small form factors with a fingertip-size hemispherical input surface (⊘10*mm*, Figure 5). The contact area between the finger and the hemisphere has a diameter of approximately 6mm. The surface is made of deformable silicone.

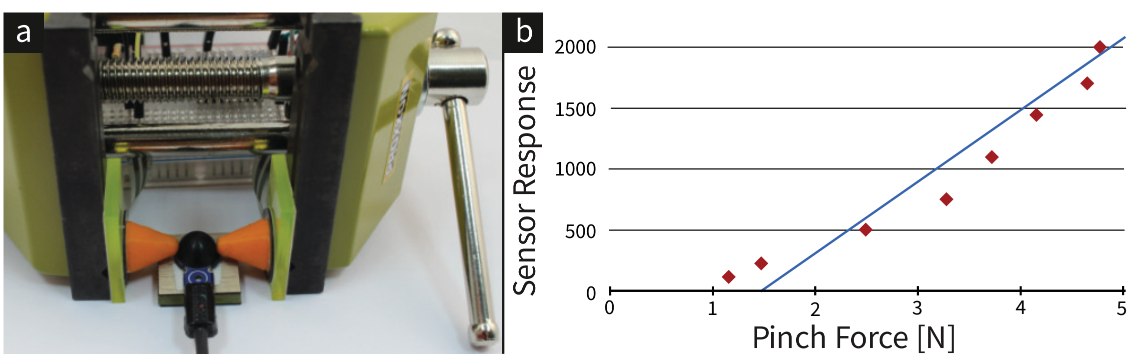

Fig. 6. Evaluation of pinch deformations: (a) apparatus; (b) sensor response for pinch forces with a fitted linear mapping function.

Table 1. Overview of DeformWear's interaction techniques

Interaction Technique	Pressure	Shear	Pinch	Example Output
Fluid Pan & Zoom	Zoom-in	2D Panning	Zoom-out	Smartwatch
Gestures & Gesture Modes	Part of Gesture	Part of Gesture	Part of Gesture	Smartwatch
	Quasi-mode	2D Gesture	Quasi-mode	Audio
Six-Way Navigation	Hierarchy Down	Up/Right/Down/Left	Hierarchy Up	Smartwatch
	Action (Jump)	Up/Right/Down/Left	Action (Crawl)	VR Headset
Radial Selection & Navigation	Hierarchy Down	Radial Input	Hierarchy Up	AR Glasses
Force-Sensitive Pointer Input	Action (Draw)	2D Pointing	Action (Erase)	Remote Display

The *bracelet* and *ring* prototypes (Figure 2a&b) consist of a custom mount (20x20x2 mm) for the hemispherical input sensor. A band of thin Velcro allows for fast and easy affixing to the user's finger or wrist. The *pendant* contains a 3D-printed mount (30x35x2 mm), which is attached to a necklace (Figure 2c). Its aesthetic design was inspired by existing pendants. Future devices could be embedded in various surface materials and be offered in different sizes to fit the user's body. In all prototype mounts, the sensor surface protrudes from the mount by 6mm. The sensor is tethered either to a computer or a battery-powered Raspberry Pi 2 over USB.

DeformWear input can be used along with various output devices. This includes auditory output or visual output on existing wearables, such as smartwatches or head-mounted displays. Furthermore, auditory or haptic output could be integrated right within the input device. DeformWear can also be used to control mobile handheld devices, e.g., while they are inside a bag or pocket, or stationary devices, such as TV sets or gaming consoles. We use a wrist-worn 2.2" display to provide visual output in a smartwatch form factor. Alternatively, it connects to Google Glass and Oculus Rift for visual output on a head-mounted display, or it can provide audio output through headphones.

5 INTERACTION TECHNIQUES

In the following, we illustrate the novel interaction capabilities of DeformWear by presenting five interaction techniques (see Table 1), which leverage deformation input on the tiny device surface. The techniques offer support for navigation, gestures, and pointing – important classic tasks for mobile HCI that were difficult to perform with existing two-dimensional input techniques on tiny wearable devices. A set of example applications demonstrate the use of DeformWear in conjunction with important wearable output devices, including smartwatches, head-mounted displays, and audio feedback.

5.1 Fluid Pan-and-Zoom for Small Displays

Panning and zooming [3] are frequent and important interactions to navigate in information spaces, e.g. city maps, documents, or photos. The small screens of wearable devices make them paramount interactions for wearables. Most wearable devices separate pan and zoom into consecutive actions, because they only allow for two-dimensional input. In contrast, DeformWear allows for continuous, precise and simultaneous pan and zoom, due to its rich three-dimensional input space. Two-dimensional shear deformation is used for panning. Pressing is used for zoom-in, and pinching for zoom-out. Notably, this intuitive mapping is made possible through our investigation of pinch deformations, because the sensor by default did not provide a form of input opposite to pressure. The applied deformation forces are mapped to the speed of panning and zooming.

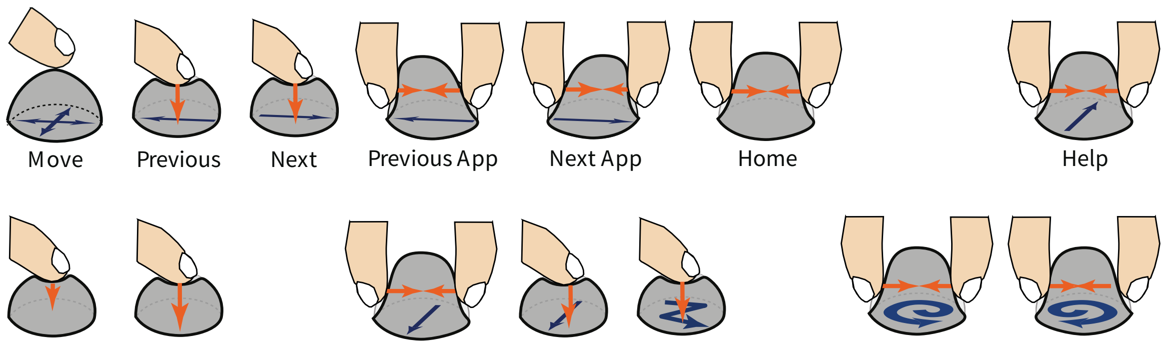

Fig. 7. Gestures for smartwatch interactions. Pressure and pinch forces are drawn in orange; shear forces in blue.

We implemented one-handed smartwatch input for navigating maps (Figure 1b). The DeformWear device is located on a finger of the same hand where the watch is worn. We have empirically chosen a threshold of 1.25 N to prevent accidental zooming. The amount of force is linearly mapped to the speed of the zooming.

5.2 Gestures and Gesture Modes

Gestures are a fast way to enter commands on wearable devices, e.g., to accept/decline calls or to control a music player. However, tiny wearable devices are commonly too small to support a large set of gestures. The three deformation primitives of DeformWear allow for a large three-dimensional gesture space, which allows for more unique gestures and more expressive mappings. To illustrate this, we present in Figure 7 a gesture set for common operations on smartwatches. The gestures were designed by three interaction designers to demonstrate the expressivity of multi-dimensional deformation input. Navigation actions are based on shear input. The additional pinch and pressure forces help to resolve ambiguous commands, e.g. moving inside the app and between apps. Pinch invokes navigation through apps, while pressure executes application-specific commands. The gesture set distinguishes between light pressure for selection and hard pressure for execution. Copy and paste are inspired by picking an element (pinching) and placing it (pressing) somewhere else. Undo and redo are inspired by setting the time on a watch crown. The amount of shear circles specifies how many actions should be undone or redone. As demonstrated, the gestures can combine pressure with shear and pinch with shear. This allows for versatile mappings that can be quickly executed and easily memorized. The small movements involved support discreet gesture input. Furthermore, the gestures can be performed one-handed, when DeformWear is worn on the finger or is attached to a graspable object.

To further extend these 2D shear gestures with quasi-modes, we introduce *Gesture Modes*. Quasi-modes are selected by adding pressure or pinch while performing the shear gesture. Hence, the same two-dimensional shear gesture can be mapped to different (ideally related) commands. The gestures therefore remain simple and easy to remember despite the larger command set. Experienced users can even change the quasi-mode during a continuous shear gesture by changing the amount of pressure or pinch. This is especially useful for commands that are related and often performed in a sequential order (e.g. fast forward, skip song and skip album; see Figure 8c).

As an application example, we implemented an eyes-free audio player (Figure 8a). Shearing left or right continuously seeks backwards or forwards in a song. The amount of shear force is mapped to the speed of the seeking, allowing for fine-grained control. To seek through the list of songs in an album, the user adds a light pressure force (1 N to 2.5 N). To seek through all albums, the user presses more firmly while doing the seeking gesture (>3.5 N). Experienced users can smoothly navigate through their music: they integrate the actions of fast forwarding within a song, skipping songs and skipping albums, simply by increasing or decreasing the amount of pressure during the shear gesture (Figure 8c).

5.3 Six-Way Navigation

Mobile icons, pictures and other data are often shown in a 2D grid and clustered in albums and folders. The two-dimensional input of most wearable devices is not sufficient to browse these structures and requires additional buttons (e.g. “home”, “back”, “preview”, “open”). DeformWear allows for navigating up/right/down/left using shear deformations and navigation through the hierarchical structure: Pressure deformation enters a deeper level, whereas pinch deformation returns to a higher level. Hence, it provides navigation in six directions on the same tiny input surface. The amount of shear force in each direction can be mapped to the navigation speed. The different force levels of pressure and pinch allow for different commands, e.g. light pressure previews the selected item and a stronger force opens it. Six-way navigation also supports precise, speed-controlled movement of an avatar through games similar to an analog stick.

We realized this interaction technique in two application examples. First, we implemented this technique for occlusion-free navigation in a photo gallery for smartwatches (Figure 9a). Second, we implemented a controller for Super Mario 64 (Figure 9b). Shearing moves Mario through the level with a controlled speed, light pressure (1 N to 2.5 N) makes him jump, strong pressure (>2.5 N) double jump, and pinching (>1.25 N) makes him crawl.

5.4 Radial Selection & Navigation

Shear input not only provides four directions, but also allows for radial input. This interaction technique is useful for applications that only require a single degree of freedom, e.g. to set a time, a position in a progress bar, or an item in a radial menu. The shear angle chooses an item, which is selected as soon as the shear force exceeds a threshold. As for six-way navigation, pinch and pressure allow navigation through multiple stacked levels. For example, this can be used to offer a higher number of menu items without sacrificing fast selection.

We implemented a stacked radial menu for a messaging application with our ring prototype (Figure 1c). It offers fast and discreet menu input for a head-mounted display while supporting a large number of menu items. Each menu level contains eight menu items. A selection is highlighted with a light shear force (1 N to 2 N) and selected with a medium force (>2 N). The stacked menu levels contain standard mail options, quick-reply templates, and sharing options.

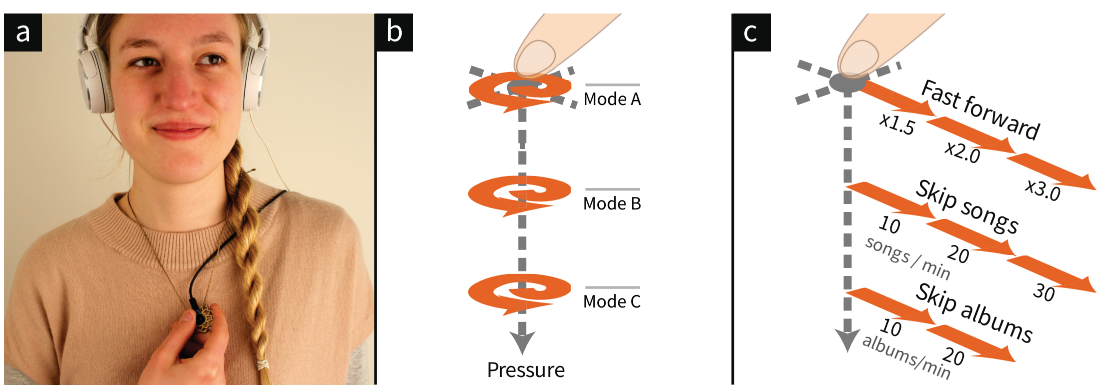

Fig. 8. Gesture Modes increase the expressivity of gestures: (a) Controlling a music player. (b) The same shear gesture can be mapped to different commands using pressure. (c) Example mapping of continuous shear gestures for a music player.

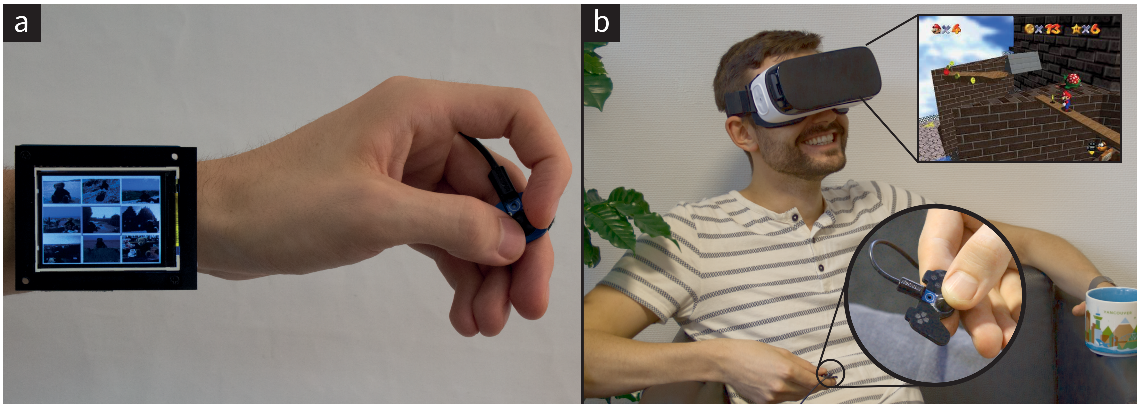

Fig. 9. Example applications of six-way navigation: (a) occlusion-free navigation in a photo gallery for smartwatches; (b) DeformWear as a keychain controller for mobile VR gaming.

5.5 Force-Sensitive Pointer Input

Shear input on isometric joysticks has been used as a pointing input on notebooks [40]. Pointing input is useful for wearable devices, e.g. for drawings and annotations on head-mounted displays or slideshows. The form factor of DeformWear allows for these scenarios using continuous, high-resolution shear input. In contrast to isometric joysticks, DeformWear supports high-resolution pressure or pinch input during the pointer movement, hence enabling force-sensitive pointing input. For example, the user can draw with varying stroke width by manipulating the pressure deformation while moving the pointer. Similarly, pinch deformations allow for a force-sensitive second command, e.g. an eraser with varying diameter.

We implement an annotation application for projected presentations. Shearing moves the pointer; pressure changes the pen width and pinch the width for the eraser. We chose a low force of 1.25 N as a required threshold for annotating and erasing.

6 EVALUATION

To assess the feasibility and usability of the DeformWear input principle and of the interaction techniques that were illustrated above, we empirically investigated the following questions:

(1) How performant and precise is deformation input on various body locations?
(2) How many levels of deformation can be reliably distinguished and held by users?
(3) Can it be used in mobile scenarios like walking?
(4) Can users combine shear with pressure or shear with pinch in one gesture?

We evaluated the DeformWear prototypes in four tasks: first, we evaluated the basic performance of pressure, shear and pinch deformations (T1+2); next, we evaluated gestures that combine shear with pressure or pinch (T3); finally, we evaluated the combination of relative shear and absolute pressure (T4). All tasks were evaluated on three body locations, while standing and walking. The evaluation was split into two sessions to avoid fatigue effects. The average duration for session 1 was approximately 90min, and for session 2, 60min. Session 1 comprised tasks 1&4; session 2 comprised tasks 2&3. A two-month break between sessions prevented training effects.

6.1 Participants

We recruited 12 participants for session 1 (6f, mean age 25.3y) and 12 for session 2 (6f, mean age 24.8y; 8 participants from session 1). Participants received a small compensation for their participation.

6.2 Setup and Apparatus

The participants were standing and walking on a treadmill (Horizon Fitness Paragon 6) to allow for a controlled movement speed. User input and target were visualized on a 24" display (1920x1200px) that was affixed in front of the treadmill at approximately 1 m distance from the user. We chose to evaluate DeformWear on three common locations for wearables: finger, wrist, and pendant. Participants could choose their preferred grasp for the bracelet and their preferred side for the ring and bracelet condition to achieve optimal results for each deformation task. At any point during the study, participants could freely decide with which finger they operated the device. Furthermore, all input was performed without looking at the input device. The raw input from the sensor was logged for later analysis. Participants were free to take breaks at any point during the study, but none of the participants decided to do so.

6.3 Task 1: Performance of Shear and Pressure Input

In a target acquisition task, we investigated the basic performance and accuracy of pressure and two-dimensional shear deformation input. Task 1 considers deformations that can be performed by a single finger, i.e. pressure and shear. Participants performed the task with *three devices* (bracelet, pendant, and ring) in *two activities* (standing and fast walking at 4 km/h). Participants were to acquire two-dimensional shear *deformation targets* (up, left, down, right) and pressure targets. The setup was similar to prior force studies on rigid mobile phone displays [22]. For each direction (pressure and up/left/down/right shear), we evaluated *six targets*. The targets comprised two target widths and three target distances. As target widths we chose 1.5 N (representing three targets in each direction) and 0.75 N (representing six targets in each direction). They represent easy (1.5 N) and challenging tasks (0.75 N) for wearable devices. The target distances cover low (1.25 N), medium (2.75 N), and high forces (4.25 N).

Participants were asked to acquire the targets as quickly and precisely as possible. The target was visually highlighted as soon as it was acquired. After a dwell time of 1s, the target was successfully selected. Then, after the user had reset the input (force less than 0.2 N), the next target was activated. Each target was repeated three times.

This setup resulted in *3 (device conditions) x 2 (activities) x 5 (directions) x 6 (targets) x 3 (repetitions) x 12 (participants) = 6,480 trials.*

6.4 Task 2: Performance of Pinch Input

Task 2 evaluates the basic performance and accuracy of pinch deformation. Compared to T1, this type of input requires at least two fingers for the interaction. We changed the target space to better reflect the sensitivity range of our deformation sensor. As pinch force levels we used low (2.3 N), medium (3.3 N), and high forces (4.4 N). The target widths were adjusted to reflect the smaller target space (1 N and 0.5 N). Otherwise, the same setup and conditions were used as in T1.

This resulted in *3 (device conditions) x 2 (activities) x 6 (targets) x 3 (repetitions) x 12 (participants) = 1,296 trials.*

6.5 Task 3: Shear+Pressure and Shear+Pinch Gestures

Task 3 investigates the basic performance and accuracy of gestures that combine pressure or pinch deformations with shear deformations, similar to the gestures in Figure 7. The setup was the same as in T1, but the participants needed to combine two deformation primitives at the same time and hold them for a dwell time of 1 s. Participants performed the task with the three demonstrator devices (bracelet, pendant, and ring) in two activities (standing and fast walking at 4 km/h), i.e. in six conditions. For pinch and pressure deformation, the target distances were the same forces as in T1 and T2 with the larger target width. For shear, the targets required a medium force (2.75 N) with 1.5N target width in one of the four dimensions. Each target was repeated three times.

This setup resulted in *3 (device conditions) x 2 (activities) x 4 (directions) x [3 (pinch distances) + 3 (pressure distances)] x 3 (repetitions) x 12 (participants) = 5,184 trials.*

6.6 Task 4: Pressure-Sensitive Relative Shear Deformation

This task studies relative movement using shear deformations while holding a pressure level, e.g. as required for force-sensitive movements. Participants were asked to hold the pressure in an absolute force range and use shear to navigate a target to the center of the screen. The target could only be moved when the participant applied a pressure within the specified range. The pressure ranges were low (0.5 N to 2 N), medium (2 N to 3.5 N), or high force (3.5 N to 5 N). The targets to navigate using shear input had a distance of 500px from the center and were distributed in eight directions around the center ($\angle 0, 45, 90, \ldots, 315$). The 2D shear input moved the target with a speed of $350 Px/Ns$. In an informal pre-study with 5 users we identified this speed as a good balance between speed and control. The target could not leave the visible display area. As in T1, participants performed the task with the three demonstrator devices (bracelet, pendant, and ring) in two activities (standing and fast walking at 4 km/h), i.e. in six conditions. For each target the user made three repetitions.

This setup resulted in *3 (device conditions) x 2 (activities) x 3 (pressure ranges) x 8 (shear directions) x 3 (repetitions) x 12 (participants) = 5,184 trials.*

In each session the order of tasks was counterbalanced. Within each task, the order of device conditions was counterbalanced and all targets were randomized to avoid bias. The order of activities (standing and walking) was counterbalanced between participants to avoid learning effects, but constant for each participant to avoid fatigue. In all tasks, participants had unrestricted practice time before each test condition to make themselves familiar with the device and the activity, until they felt comfortable with the task (on average 3 minutes per task).

6.7 Results

Our analysis focuses on task completion time and errors. We chose the task completion time as the most commonly used performance measure. It captures a set of realistic factors: complexity of the primary task, walking, and precise target acquisition (due to the time penalty from under- or overshooting). Moreover, it is better suited for statistical analysis compared to the low number of error trials. All data is reported without any outlier filtering. All trials except one could be successfully accomplished by all participants. The exception was for the bracelet while walking, when one participant wanted to skip a difficult target; we removed this trial from the dataset.

6.7.1 Task 1. The performance results of T1 can be found in Figure 10a+b and d+e. In the *standing* condition, all tasks had average task completion time of less than 2.2 s for pressure and 2.7 s for shear deformations, including the 1 s dwell time. The bracelet was the fastest device with an average task completion time of 1.615 s. For the ring it took 1.701 s, and for the pendant 1.721 s. These small differences were not statistically significant.

A paired t-test shows significant differences between the task completion times while standing vs. walking ($t(3239) = 12.16, p < 0.001$). While *walking*, the task completion time increased on average by 20.6%. This increase was surprisingly small for the ring (8.1% longer) and the pendant (7.8% longer). In contrast, the increase amounted to 46% for the bracelet. It is noteworthy that the bracelet had the best performance of all three devices in the standing condition, while it had the lowest performance in the walking condition. An ANOVA identified significant main effects between the devices ($F(5, 66) = 10.61, p < 0.001$). Bonferroni corrected post-hoc tests found significant differences between using the bracelet while walking and all other walking conditions.

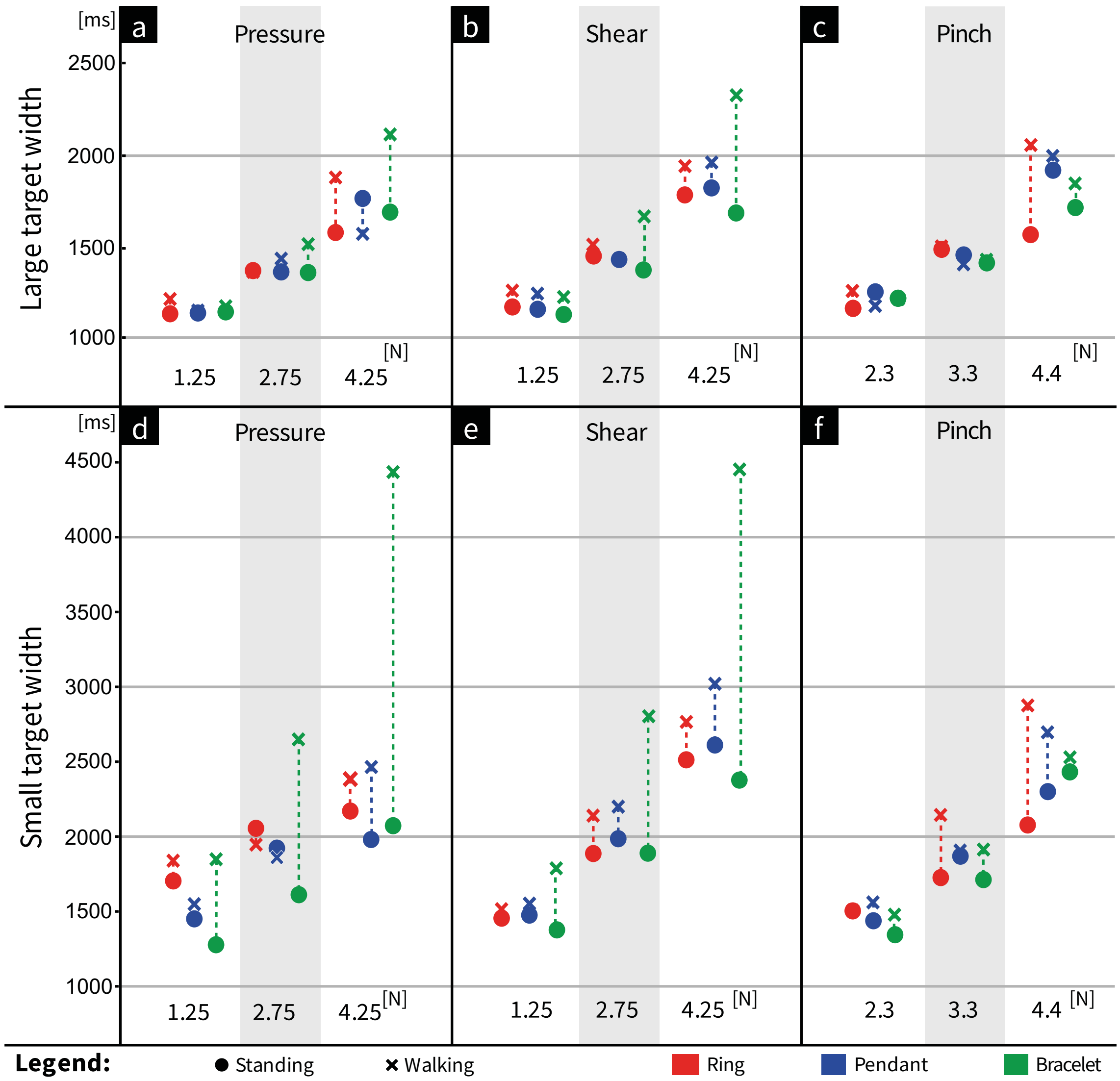

Fig. 10. Average task completion times from T1 (pressure and shear) and T2 (pinch). All times include a 1s dwell time.

We calculated the number of errors, i.e. how often participants dwelled for 1 s on the wrong target. The error rate was 0.3% while standing and 0.5% while walking.

6.7.2 Task 2. The performance results are depicted in Figure 10c+f. The average task times were below 2.5 s in the standing condition and below 2.9 s in the walking condition. A paired t-test shows significant differences between the task completion times for standing and walking ($t(647) = -4.5946, p < 0.001$). While walking, the task completion time increased on average by 9.8%. The error rate was 0.15% for the standing and 0% for the walking conditions.

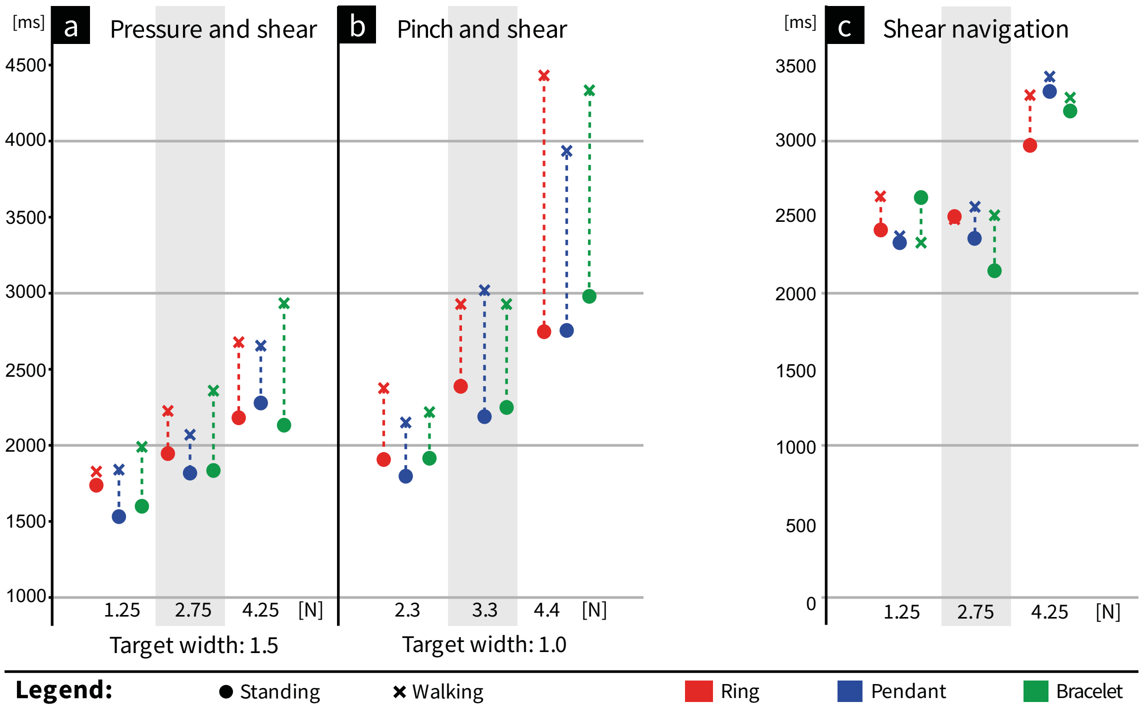

Fig. 11. Average task completion times of T3 and T4: (a) Combined pressure and shear deformation targets and (b) combined pinch and shear deformation targets in T3. All times reported in (a&b) include a 1 s dwell time. (c) Average task completion times in T4.

6.7.3 Task 3. All *shear+pressure* combinations were acquired in less than 2.2 s in the standing condition. The average task time was 1.9 s and the error rate 3.9%. In the walking condition, the task completion time increased by 20.6%. A paired t-test shows significant differences between standing and walking conditions ($t(1295) = -9.8532, p < 0.001$).

All *shear+pinch* combinations were acquired in less than 2.9 s in the standing condition. The average task time was 2.3 s and the error rate 5.1%. In the walking condition, the task completion time increased by 35.2%. A paired t-test shows significant differences between standing and walking conditions ($t(1295) = -11.699, p < 0.001$).

These results show that pressure and pinch deformations can be combined with simultaneous two-dimensional shear deformation input. For approximately the same index of difficulties, shear+pressure and shear+pinch perform with similar mean times.

6.7.4 Task 4. The performance results of T4 are depicted in Figure 11c. The mean task completion time was 2.71 s in the standing condition and 2.82 s (+4.1%) in the walking condition. The devices show similar average completion times. We did not find a statistically significant difference between the standing and walking conditions, nor between the three devices.

We compared task completion time for the three different pressure ranges. The mean times were similar for low force (2.51 s) and medium force (2.49 s), but considerably higher for high force (3.31 s). An ANOVA identified significant main effects between pressure ranges ($F(1, 11) = 10.961, p < 0.05$). Bonferroni corrected post-hoc tests found significant differences between the highest pressure range and the two others. This indicates that combining shear with high levels of pressure is significantly more challenging for the user.

These results show that all devices allow for two-dimensional shear input while the participant is holding a pressure at one of three levels. Despite the complex combinatory tasks, participants still achieved high input performance. The increased task completion time for high-pressure inputs should be considered when fast execution times are required.

6.7.5 Input Strategies. We observed different input strategies during the tasks. For input on the wrist, 75% of participants used the index finger and 25% the thumb. For the pendant, 83% used the thumb and 17% the index finger. Pinch input was performed with both the thumb and the index finger by all participants. We also observed different grasps of the pendant: 6 participants (50%) used it for one-handed input, similar to the ring; 3 participants (25%), used two hands; another 3 participants (25%) switched between one- and two-handed use during pressure and shear deformations. For pinch input, eleven participants (92%) interacted on the pendant two-handed. One participant (8%) switched hands during the experiment. For the ring, all participants interacted one-handed on their dominant hand for shear and pressure tasks. For pinch forces, 3 participants (25%) attached the device to their middle finger. One used one-handed input with thumb and index finger for all targets, while the other two switched between one and two-handed input. One participant commented: "I have to use the other hand for the smallest targets [highest force], because I don't have enough strength" [P12]. The other 9 participants (75%) attached the device to their non-dominant hand and interacted with their dominant hand.

7 DISCUSSION AND DESIGN IMPLICATIONS

Based on the evaluation results and on lessons we have learnt during the iterative design and prototyping, we derive design implications for DeformWear. We discuss the influence of form factor and body location, derive implications for our interaction techniques and provide detail on the comfort of deformation input on wearable devices.

7.1 Form Factor and Locations

The findings of the empirical study demonstrate that deformation input is fast and precise for all devices in the standing condition. In the walking condition, we found significant differences between the devices. While the ring and pendant had only a small increase in their average task completion time (7.1% and 8.1%), the average task completion time on the bracelet increased by 20.6%. This shows that form factor and body location have a major influence on the performance of deformation input. In the following, we will discuss the results of the study and derive design implications for each location:

7.1.1 Ring. Input on the ring showed a good performance, combining low task completion times and a low number of crossings, for both standing and walking conditions. This makes it an appropriate candidate for interactions that are likely to happen during movement, e.g., on fitness devices. The ring can be used for one- or two-handed interactions. All participants chose to use the ring as a one-handed input device for shear and pressure input; for pinch input, one-fourth of the participants opted for one-handed input, pinching the sensor with the thumb and the middle finger. Hence, all deformation primitives can be performed with one-handed input, but the majority of participants used the other hand for pinching. Therefore, interaction designers should carefully choose the required amount of pinch deformations for one-handed scenarios. Last but not least, the ring was rated as the favorite device by the majority of participants.

7.1.2 Pendant. The performance of input on the pendant was similar to the performance of the ring. Hence, it can be characterized as a good device form factor both for standing and walking. During the study, the pendant was grasped in various ways: while one-handed input was most frequent, a considerable number of participants grasped it with the non-dominant hand and operated it with the index finger or thumb of the dominant hand. Therefore, the device needs to be comfortable and easy to hold in these grasp styles.

7.1.3 Bracelet. The wrist turned out to be one of the best locations for deformation input when the user was standing. This makes it a great addition to smartwatches. Added onto the bezel or the wristband of a smartwatch, DeformWear enables occlusion-free input. However, we identified a significant performance drop for difficult targets while the user was walking. This might relate to the fact that the input location requires the user to bring together both hands in front of the body; this could conflict with naturally swinging the arms as happens while walking. As a remedy for improved wrist input while walking, we recommend that the interface automatically adapt to the activity level: it should switch to an easier interface when walking is detected, e.g., by using an accelerometer. For example, a menu can show only the most frequently used items during walking. If this is not an option, an additional input sensor for one-handed interaction (e.g., on the finger) could be used to interact with the smartwatch.

7.1.4 Input while Walking. Engineers and designers should carefully consider in which mobile activities the device is to be used. For devices that are designed for use while walking, one-handed interactions should be preferred to avoid conflicting with the natural movement of the arm. They can be either attached to the finger or temporarily grabbed for input, e.g. as we have realized with the pendant device. These forms of input have been shown to offer an input performance while walking that is almost as high as in an immobile setup. Our study has not studied interaction while running; this remains to be investigated in future work.

7.2 Interaction Techniques

The four tasks of our user study evaluate single-dimensional and multi-dimensional deformation input. Results from tasks 1 and 2 showed that pressure, shear and pinch deformations are expressive input dimensions, allowing users to reliably distinguish and hold at least six different levels. The results from task 3 show that participants can combine and hold a low, medium and high pressure or pinch deformation simultaneously with a two-dimensional shear force. In addition, task 4 shows that participants can use shear deformations for relative movements while holding one of three pressure ranges. Based on these findings, we derive design implications for our deformation-based interaction techniques:

7.2.1 Fluid Pan and Zoom. Continuous panning and zooming can be performed precisely with six speed levels. Task 3 combined panning (shear) with zoom input (pressure or pinch). This shows that the user can zoom in and out in three different speeds while panning the map.

7.2.2 Gestures and Gesture Modes. Our studies show that DeformWear allows linear gestures with six different force levels for pressure (T1), 2D shear (T1) and pinch (T2) deformations. Gestures inside the rich three-dimensional input space are also supported, by combining 2D shear input with either pressure or pinch (T3).

Gesture Modes can have at least six different modes, three for pressure and three for pinch. Task 3 shows that users can perform two-dimensional shear input while holding a pressure or shear deformation at one of three force levels. These findings directly translate to performing a linear shear gesture in a specific mode, e.g. in our music player example. The most frequent commands should be mapped to low- and medium-pressure modes. Less frequent commands can be mapped to input types with a higher task completion time, e.g. the modes with strong pressure or strong pinch input.

7.2.3 Six-Way Navigation. The results of tasks 1 and 2 show that DeformWear allows for interaction in all six directions. Each of the six directions allowed for six different force targets. These can be either mapped to six speed levels or to six different commands (e.g. select, preview, open).

7.2.4 Radial Selection and Navigation. The results of task 4 suggest that radial selection is possible for eight directions. This allows for radial menus with eight menu items. Tasks 1 & 2 show that pressure and pinch allow for navigating though multiple stacked levels. The upper limit of radial items is yet unknown; finding it remains for future work.

7.2.5 Force-Sensitive Pointer Input. Task 3 shows that DeformWear allows for combining shear with pressure or pinch deformation input. Task 4 shows that continuous pointer movement is possible in eight directions while continuously holding a constant pressure level. Common pressure input should map to low and medium forces, because higher pressure force requires more time for task completion. Pinch deformation input can be mapped to a secondary command and shows a similar performance when combined with shear input (task 3).

7.3 Comfort

Comfort is an important factor to consider when designing force-sensitive devices, since pressure is passed on to the underlying body part. DeformWear uses only small pressures (< 5 N). These forces are perceived by the interacting finger and by the body at the location of the input surface. The forces are distributed to the area under the input surface. Smaller input devices will distribute the force to smaller parts of the body, creating higher localized pressure. This is unproblematic for DeformWear devices that are embedded in objects (e.g. watches, buttons, or jewelry), since they distribute forces to a larger area. Very small devices worn directly on the skin should avoid highly pressure-sensitive body parts, e.g. the top of veins. Furthermore, extremely soft body parts should be avoided, because the deformation of skin and flesh underneath the device reduces the effective force on the sensor in an uncontrolled way, hence reducing the sensitivity.

8 LIMITATIONS AND FUTURE WORK

We opted for a controlled study to analyze and understand the novel characteristics of DeformWear. The study gives first insights into deformation input in mobile activities: Our analysis discovered significant differences in performance between the devices while walking. Furthermore, it showed that participants prefer different placements and use different input strategies. As a next step, future work could build upon these results and analyze the performance of DeformWear in field studies, for example by comparing two-handed and one-handed input with varying walking speeds and while running.

Our evaluation focused on input performance and does not intend to make claims about output. We opted for a neutral device configuration to bias the input task as little as possible: a stationary display is always readily visible, independently of the user's hand and arm pose. A wearable display might have some effect on task performance, as it might require the user to adopt a slightly different posture for observing visual output. Due to our focus on input, we did not consider haptic output and stiffness changes, e.g. achieved through pneumatic jamming [9] or programmable gel [24].

Our DeformWear prototypes all have a hemispherical shape. This shape allows the user to use taction for finding the center. It affords interaction in all directions. Other shapes could create different physical affordances, e.g. to guide the finger in certain directions. The grip on the device can be enhanced with a rough surface structure. This improves interaction with wet or sweaty fingers that are likely in outdoor and fitness scenarios. The sensor we have used for our prototypes protrudes by a few millimeters and is hemispherical. Advances in sensors make it very likely that in the future, wearable force sensors can be realized in a very thin and fully flat form factor [37, 51]. It will have to be investigated how such a change in form factor affects interaction performance.

Finally, we focused on enabling expressive deformation input on various body locations, rather than avoiding unintentional input. We expect that unintentional input mostly depends on the body location and device orientation. For instance, a DeformWear device worn on the finger and facing towards the palm might conflict with grasp actions, while facing towards the back of the hand, it would not. In this case, accidental input could be avoided by rotating the ring after use. Therefore, designers and engineers need to carefully select the location where DeformWear should be worn. Finally, we expect that unintentional input results in specific temporal input patterns, which could be used to identify and remove it.

9 CONCLUSION

This paper contributed DeformWear, tiny input devices that scale down to the size of the head of a push pin. They use pressure, pinch, and shear deformations for expressive interactions with wearable computing devices. We described the interaction space for tiny deformation-sensitive wearables, illustrated possible locations for DeformWear, and demonstrated the technical feasibility with three functional device prototypes: a ring, a bracelet, and a pendant.

To show its expressive input capabilities, we presented deformation-based interaction techniques for tiny and soft wearable devices. The interaction techniques enable fluid interaction in a large input space by combining multiple dimensions of deformation. Despite the small device size, the interaction techniques help mitigate input problems on existing wearable devices. For example, DeformWear allows for fluid, one-handed navigation on smartwatches, for interaction in a large gesture space, and for discreet menu selection. DeformWear can be used as a standalone input device and as a companion device for smartwatches, head-mounted displays, or headphones.

We reported empirical findings on deformation-based input on tiny wearable devices from a controlled experiment with users. The findings detail the performance of our three prototypes worn on different body locations. The study evaluated the wearable devices in standing and walking conditions. The results show that pressure, shear, and pinch deformations enable fast and precise input and that participants were able to distinguish and hold up to six deformation levels. Furthermore, combined pressure and shear, as well as combined pinch and shear deformations, can be performed to allow for the fluid and multi-dimensional input used in our interaction techniques. The results also demonstrate large effects of one-handed vs. two-handed interaction in walking conditions. This has important implications for the choice of an appropriate body location and device form factor for DeformWear input.

Altogether, our contributions allow for further miniaturization of wearable devices by using expressive deformation input. These future devices can be worn at a multitude of body locations, are unobtrusive, and are well-suited for fast and discreet mobile interactions.

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