# DeformIO: Dynamic Stiffness Control on a Deformable Force-Sensing Display

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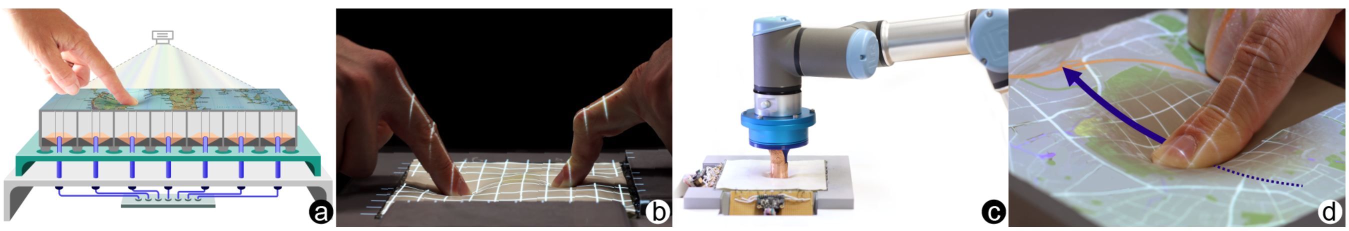

**Figure 1: DeformIO co-locates force-input and force-output on a display. (a) DeformIO supports multi-point touch and force input, while providing multi-point variable stiffness; (b) We validate and characterise DeformIO using a robot arm; (c) We conduct a user study to explore multi-point touch and force interaction with users and; (d) We describe a vision for DeformIO in our everyday lives.**

## ABSTRACT

Introducing *DeformIO*, a novel deformable display with co-located force input and variable stiffness output. Unlike prior work, our approach does not require pin arrays or re-configurable panels. Instead, we leveraged pneumatics and resistive sensing to enable force detection and stiffness control on a soft continuous surface. This allows users to perceive rich tactile feedback on a soft surface and replicates the benefits of fluid finger movement from traditional glass-based screens. Using a robotic arm, we conducted a series of evaluations with 3,267 trials to quantify the performance of touch and force input, as well as stiffness output. Additionally, our study confirmed users' ability to apply multiple force inputs simultaneously and distinguish stiffness levels. We illustrate how DeformIO enhances interaction through a vision for everyday interaction and include two implemented self-contained demonstrations.


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## CCS CONCEPTS

• **Human-centered computing** → **Touch screens**; **Haptic devices**; **Displays and imagers**.

## KEYWORDS

Force Input, Variable Stiffness, Deformable Display, Pneumatics

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## 1 INTRODUCTION AND RELATED WORK

Force has a rich history of exploration as both an input and output modality in Human-Computer Interaction (HCI). Numerous devices support force as an input [1, 9–11, 20], as well as an output [4, 15, 29, 32], but they are often explored *independently*. While prior research has emphasized the advantages of integrating input and output force modalities on a single surface, the prevailing approach

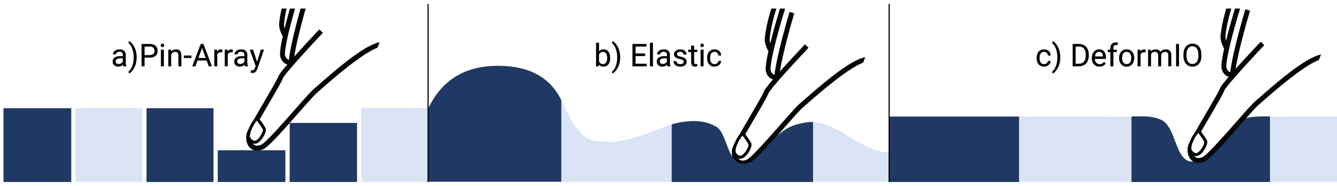


**Figure 2: Fluid finger movements on different displays. Areas of high stiffness are dark blue, with low stiffness in light blue. a) A user interacting with a re-configurable pin array display, pushing the pins below their finger down; b) An elastic display, where pressure changes distort the surface; the surface deforms downwards around the user's finger as they push in; c) DeformIO, which uses asymmetrical stiffness to maintain a flat continuous surface which deforms down around their finger as they press.**

in this field has mainly centred around the utilization of rigid re-configurable panels [3, 14, 17, 24] and pin-based arrays [12, 18, 19], however, we identify two limitations with these approaches.

First, in line with Srinivasan and LaMotte [25], *deformable* objects have soft surfaces (e.g. rubber or sponge) and are distinctly different from *re-configurable* objects with rigid surfaces (e.g. keyboard or light switch). Boem and Troiano [2] extended this concept, separating interactive devices where users re-configure rigid elements to alter their shape [6, 8, 21], from deformable devices [7, 22, 29]. Deformable devices allow for varied and diverse inputs [28], including force-augmented swipes and non-perpendicular force input. These devices offer richer tactile feedback including the surface shape change when touched by the user's finger. Therefore, we see significant interaction benefits to combining force-input and force-output on a deformable surface. Second, traditional flat, glass-based touchscreens excel in providing *fluid finger movement*, facilitating common gestures such as swipes or pinches [16]. However, displays with surface gaps, e.g. pin-based arrays (Figure 2a), or with bulges or bubbles, e.g. elastic displays (Figure 2b), lack the capability to support the continuity and fluidity of user interactions.

We identify the potential for deformable, force-input and force-output displays to enhance the interaction space relative to re-configurable displays, whilst maintaining fluid finger movement and the diverse set of gestures it enables.

A dynamic force-output modality on a deformable display is better understood as a variable stiffness surface (i.e. changing resistance to user deformation). By studying existing deformable force-augmented displays and contrasting them with re-configurable force displays, we identify two variable stiffness-related challenges:

- **C1. Force-Shape De-coupling**: Modifying an object's stiffness is well understood [29, 32], but isolating it from the object's shape is more complex. Internal forces (such as pneumatic pressure) expand the structure, like inflating a balloon [26, 34]. The key challenge is to vary a device's stiffness without altering its shape.
- **C2. Dynamic Elasticity Control**: Force displays can both resist a user pushing in, and to physically push back against them, much like a compressed spring. Some previous approaches, such as malleable devices [5, 15] lack this elasticity control, retaining their shape when stiffened instead of pushing back to their original position. Realising this push-back functionality at multiple independent points, in a deformable form factor, provides significant engineering challenges.

Table 1 compares closely related work by device capabilities. There are two categories of re-configurable displays: **rigid panel** displays [24] use actuators to augment touchscreens, maintaining fluid finger movements but limiting the number of force input and variable stiffness output points. **Pin-array** displays overcome this by breaking up the display [18, 19], enabling multi-point force input and variable stiffness, but at the cost of deformability and fluid finger movements. There are also two groups of force-augmented deformable displays. **Elastic** displays [29, 34] have dynamic elasticity control (C2) but lack force shape de-coupling (C1), while **Malleable** displays [5, 13, 15] can alter their stiffness independently of surface shape (C1) at the cost of dynamic elasticity control (C2), meaning they cannot push users back.

In this paper, we present DeformIO, the first continuous and deformable display which addresses these two challenges, while co-locating force-input and force-output. It utilises asymmetrical elasticity, which prevents the display from stretching upwards and bulging, while retaining its elasticity when pushed down (Figure 2c). We employ a pneumatic control system with internal height-restricting threads for dynamic stiffness and asymmetrical elasticity and implement a force-sensing grid for precise force measurement.

We systematically evaluated DeformIO using a robotic arm to sample the force input and stiffness output accuracy 3,267 times. A human-participant study (n=10) assessed DeformIO's ability to handle two simultaneous force inputs and users' capacity to distinguish three force levels without visual feedback. Finally, we discuss a vision of DeformIO integrated into our everyday lives, where traditional touchscreen interactions are combined with force inputs on a variable stiffness surface. We implemented two applications from this vision to demonstrate DeformIO's potential.

In summary, we have created a continuous deformable display that co-locates input and output, enabling new possibilities for force-augmented devices. It supports fluid finger movements for touch and force gestures, resulting in unique and expressive user interactions. We contribute: **(1) DeformIO**: The first continuous deformable display with co-located force-input and force-output, achieved through a pneumatic control system, internal height-restricting threads for asymmetrical elasticity, and a precision force-sensing grid; **(2) Robotic & Human Evaluation**: Findings from technical evaluations using a robotic arm to characterize our display's performance, along with human-participant studies aimed at validating users' perceptions; **(3) Vision and Applications**: We present a vision for how DeformIO style devices could be used in our everyday lives, and two implemented applications.

**Table 1: Key capabilities and challenges in closely related work. ● are displays that fully address a given capability/challenge, while a ○ indicates it is not addressed. ⊗ shows it is partially addressed (i.e. single-point input or output capability).**

| Device Name | Actuation Method | Multi-Point Force Sensing | Multi-Point Variable Stiffness | Fluid Finger Movements | Deformability | Force Shape Decoupling | Dynamic Elasticity Control |
|---|---|---|---|---|---|---|---|
| TouchMover [24] | Rigid Panel | ⊗ | ⊗ | ● | ○ | ● | ● |
| inFORCE [18] | Pin Array | ● | ● | ○ | ○ | ● | ● |
| Materiable [19] | Pin Array | ● | ● | ○ | ○ | ● | ● |
| Jamming UI [5] | Malleable (Jamming) | ○ | ⊗ | ● | ● | ● | ○ |
| MudPad [13] | Malleable (MRF) | ○ | ● | ● | ● | ● | ○ |
| GelTouch [15] | Malleable (Hydrogel) | ○ | ● | ● | ● | ● | ○ |
| ForceForm [29] | Elastic (Electromagnetic) | ○ | ● | ○ | ● | ○ | ● |
| inFlat [34] | Elastic (Pneumatic) | ● | ● | ○ | ● | ○ | ● |
| DeformIO | Asymmetrical Elastic (Pneumatic) | ● | ● | ● | ● | ● | ● |

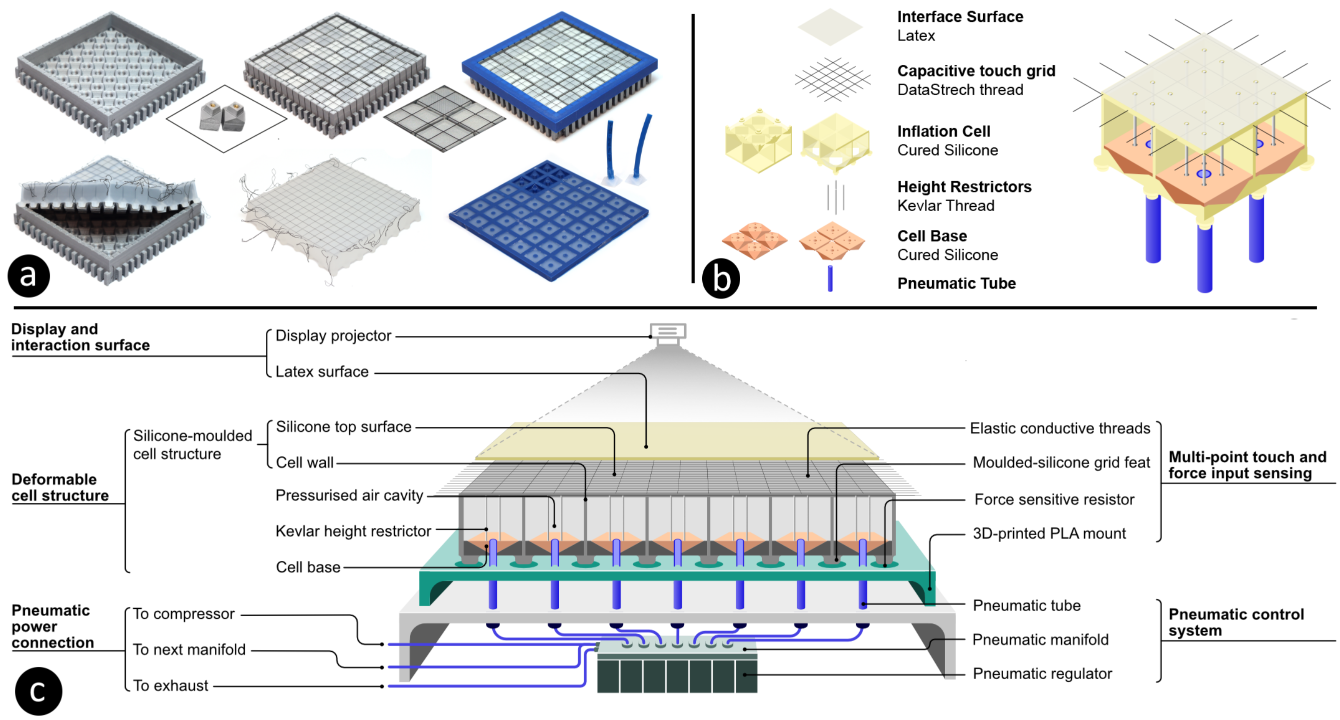


**Figure 3: Design and fabrication of DeformIO. a) the fabrication process of the 3D silicone structure; b) provides a cross-section of an individual cell; and c) shows the complete structure, including the (1) deformable cell structure; (2) pneumatic control system; (3) multi-point touch and force sensing; and (4) display surface.**

## 2 DeformIO

In this section we discuss the design and fabrication of DeformIO (Figure 1a), a novel display that addresses the challenges identified in the introduction. It uses a pneumatic stiffness control system combined with a soft silicone rubber structure, with input sensing enabled through a bespoke Force Sensitive Resistor (FSR) grid and capacitive touch matrix. The composite design overcomes the challenges, of **force-shape de-coupling** and **dynamic elasticity control**, included in Table 1. The final design is presented in Figure 3c, which shows the overall structure of DeformIO and how separate elements are incorporated into a single device, while Figure 3b illustrates a cross-section of an individual cell.

### 2.1 Enabling Deformability and Fluid Finger Movements

The core of DeformIO is the *silicone-moulded cell structure* (Figure 3c), composed of a flat 3mm thick, $140\text{mm}^2$ surface layer over a $7 \times 7$ grid of $20\text{mm}^2$ deformable cells. The cells are moulded as a single 3D structure from Ecoflex 00-30[1] silicone—the fabrication process is shown in Figure 3a. This approach provides a continuous deformable surface for user interactions. The surface of DeformIO is covered by a Latex sheet, which reduces friction and improves fluid finger movements. In the centre of the surface is the $100\text{mm}^2$ *display and interaction area* (Figure 3c), within which user inputs are detected and where the graphical output is projected from above (Figure 1d). The outer cells are the boundary ring, included in the design to improve the stiffness and sensing performance within the interaction area.

### 2.2 Force-Shape De-Coupling

The design of the deformable cell structure, combined with the pneumatic pressurisation, would normally result in unwanted bulges on the surface above pressurised cells. To prevent this, we designed DeformIO to be *asymmetrically elastic*, meaning it would not stretch or bulge upwards, even at high pressures, but still support deformable interaction when pressed. This novel approach was enabled using *Kevlar height restictors* (Figure 3c), connecting the top and bottom of each cell. The Kevlar threads are almost rigid when in tension, stopping the surface from rising, however, they collapse when compressed, providing no resistance to user forces applied into the surface. This resulted in the display being capable of resisting the internal pressure, without bulging, while retaining their deformability when pressed.

### 2.3 Multi-Point Variable Stiffness and Dynamic Elasticity Control

The *pneumatic control system* (Figure 3c) regulates each cell's pressure, enabling the multi-point, dynamic force variations across the interaction surface, by varying the pressure of individual cells. The pressure can be changed during interactions, allowing the system to vary the force applied to the user's finger even as they are pressing in, enabling dynamic elasticity control. The central $5 \times 5$ cells are independently controlled by Festo VEAB pressure regulators[2], while the outer ring of 24 cells are connected together and controlled by a single regulator to provide a boundary ring.

### 2.4 Multi-point Input Sensing

To sense a user's force input, the silicone structure was mounted on top of a grid of FSRs, which leveraged force transmissibility [33]. User's force inputs were transmitted through the silicone structure and detected at the FSR gird. During DeformIO's development, we found that the FSRs were not sensitive enough to reliably pick up soft swipes and taps across the surface. Therefore to ensure DeformIO accurately captured touch inputs, we implemented a separate touch sensing method. A matrix of elastic conductive threads was embedded within the silicone surface, following the approach by Teyssier et al. [27], capturing multi-point touch input without impacting the deformability of the silicone surface. The touch and force data are synthesised together by DeformIO to calculate the user's touch and force position.

## 3 EVALUATION

We evaluated DeformIO to characterise its performance in various conditions, by conducting a systematic surface evaluation using a robotic arm, which probed the surface a total of 3,267 times (Figure 4a), followed by a human-participant study with four tasks (Figure 4b), to understand user perceptions.

### 3.1 Systematic Surface Evaluation

DeformIO is a continuous deformable display that can be compressed at any point and can dynamically vary its stiffness across the display. We wanted to rigorously evaluate how DeformIO functioned across a wide range of various input and output conditions, given the novel construction and potential for interplay between cells. To achieve this we used a Universal Robots UR3 robotic arm[3], fitted with a NRS-6 force sensor[4], to compress the display and capture the physical response, as shown in Figure 4a. To represent a user touching the device with their index finger in an oblique manner, we 3D-printed an ellipse of size 14 mm $\times$ 20 mm as the contact area for the robotic arm [30].

The first study evaluated the $100\text{mm}^2$ interaction surface, probing 121 positions in an $11 \times 11$ grid three times, as part of a single trial. Trials were conducted at all combinations of compression depths (4 mm, 8 mm & 12 mm) and pressure settings (0kPa, 4kPa and 8kPa), for a total of $3 \times 3 = 9$ trials. Overall this resulted in the surface being probed $121 \times 3 \times 9 = 3{,}267$ times. Evaluating DeformIO across combinations of depth and pressure allows us to understand their relationship and their impact on device performance. For each probe point of the surface, DeformIO's **surface stiffness**, **force sensing accuracy** and **touch sensing** were measured. To do this, the surface was compressed to the required depth, and held still for three seconds, over which time the measured values were averaged.

Figure 4c shows DeformIO's ***surface stiffness*** for all nine trials, demonstrating how cells within the interaction area present a continuous stiffness and that structural elements such as the cell walls are not detectable in the results. The ***force sensing accuracy*** of DeformIO is presented in Figure 4d, showing the difference between the robot arm reading and DeformIO's reading for all nine trials. The device accuracy was best at 0kPa and 4mm compression depth ($M$=0.63N, $SD$=0.43N), showing the potential for high precision input sensing. However, as compression depth and pressure increased the accuracy reduces and variations increase. This may be caused by changes in force-transmissibility under these conditions.The total average RMS error across the whole surface during the nine ***touch sensing*** trials was low and consistent ($M$=2.3mm, $SD$=1.25mm). The maximum RMS error over all tests was 6.4 mm,

[1]Ecoflex™ 00-30 Website: https://www.smooth-on.com/products/ecoflex-00-30/
[2]FESTO VEAB Pressure Regulator Data Sheet: https://www.festo.com/media/pim/295/D15000100123295.PDF

[3]Universal Robots UR3 robotic arm Specifications: https://www.universal-robots.com/media/240787/ur3_us.pdf/
[4]Nordbo NRS-6 Force Sensor: https://www.universal-robots.com/fi/plus/products/nordbo-robotics/nrs-6-forcetorque-sensor-kit/

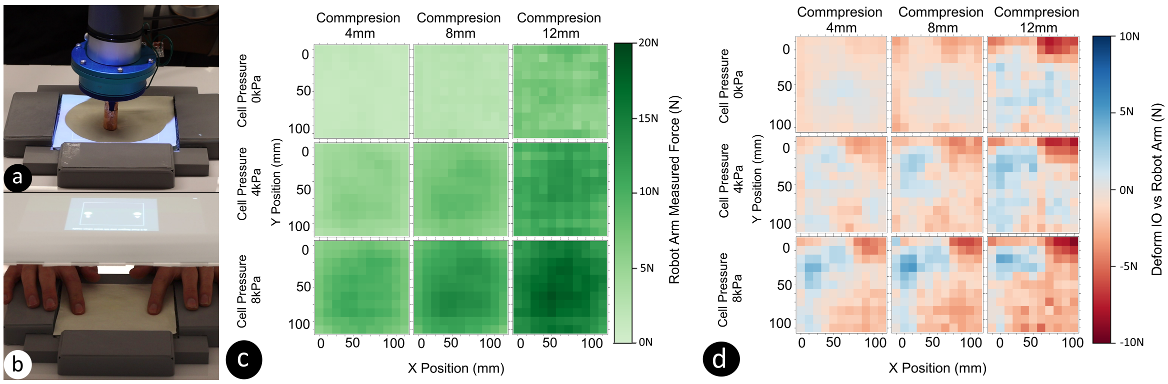


**Figure 4: DeformIO evaluation: (a) the robot arm probes the surface of DeformIO; (b) a user performs a multi-point Surface Stiffness Perception task, with the device obscured from view; Heat maps showing the results of (c) the surface stiffness of DeformIO measured by the robot arm, and; d its force sensing accuracy, compared against the robot arm.**

less than half a finger width [30]. In a small number of tests (0.6%) DeformIO did not detect a touch had occurred at all.

## 3.2 Human-participant Study

The systematic surface evaluation characterised the performance of DeformIO, however, it did not provide insights from a user perspective, nor test our **multi-point capabilities**. To address these limitations, we conducted an empirical human participant study with 10 participants (8 males and 2 females, ages *M*=23.1, *SD*=2.51). The goal was to evaluate the multi-point input and output capabilities, and to investigate users' perceptions of the device. The study contained three tasks, and took one hour to complete. Participants received £10 as compensation for their time.

*3.2.1 Task 1: User Force Input.* This task evaluated **multi-point** force input. Participants simultaneously applied two target forces onto DeformIO, with each of their index fingers. The target force was indicated by the size of a circle, with visual feedback provided by a red circle under their finger that changed size with their applied force. When the applied force was within 10% of the target force, that circle changed colour to green; once both applied forces were within target ranges simultaneously the task was completed. There were three target force levels (low: 1N, medium: 2.5N, and high: 4N), giving nine combinations that were repeated three times each, resulting in $3 \times 9 = 27$ trials.

Participants were able to input both target force levels simultaneously with very high accuracy (*M*=96%, *SD*=4%), demonstrating that DeformIO could detect multiple different force inputs simultaneously. Combined with the results from the systematic surface evaluation, this demonstrates the accuracy of DeformIO's force sensing across the surface and the functionality to capture multi-point force inputs of different magnitudes.

*3.2.2 Task 2: Surface Stiffness Perception.* This task evaluated DeformIO's presentation of distinct stiffness levels in both **single point** and **multi-point** conditions. DeformIO outputted two stiffnesses that participants felt to answer which, if either, they thought was stiffer. There were three stiffness levels (low: 0kPa, medium: 4kPa, high: 8kPa), giving nine combinations that were repeated three times, resulting in $3 \times 9 = 27$ trials presented in random order.

The task was split into two blocks. In block 1, the two stiffnesses were presented consecutively. The display started at medium stiffness and the participant pressed into the surface. DeformIO then outputed the stiffnesses consecutively, each for four seconds. In block 2, the two stiffnesses were presented simultaneously at two set points on the display, while the display and the participant's hands were obscured from their view with a cover (Figure 4b).

For block 1, participants consistently identified the stiffer of the two options (*M*=98%, *SD*=2%), demonstrating accurate perception of the changes in stiffness. In block 2, the stiffer option was selected correctly majority of the time (*M*=70%, *SD*=30%). Perception of the difference in stiffness improved when the cell pressure difference was 8kPa (*M*=87%, *SD*=13%), compared to a difference of 4kPa (*M*=66%, *SD*=21%) or when the cell pressures were the same (*M*=61%, *SD*=39%).

*3.2.3 Task 3: Surface Continuity.* The final task aimed to understand participants' perception of the surface continuity while performing fluid finger movements. Participants performed swipe/drag gestures with two different levels of force (low: ≈1N and high: ≈4N) and in two directions (left and right) on three stiffness levels (low: 0kPa, medium: 4kPa, high: 8kPa), for a total of $2 \times 2 \times 3 = 12$ trials. After each interaction participants were presented with two 7-point Likert questions asking '*To what extent was swipe interaction easy to perform on the screen? (Very Hard⟶Very Easy)*' and '*To what extent did the display feel like a continuous surface? (Not at all⟶Completely)*'.

Participants reported a moderate level of ease across all conditions when swiping (*M*=4.4, *SD*=2.0), while also rating swiping as very easy when pressing with soft force (*M*=5.7, *SD*=1.3) across all stiffness's, however when pressing harder during the swipe (*M*=3.3, *SD*=1.7) it became more difficult. Perception of the continuousness of the display was rated moderate as well (*M* = 4.7, *SD*=1.9), with a similar but less significant split with soft swipes (*M*=4.8, *SD*=1.7) being perceived as more continuous compared with hard swipes (*M*=3.3, *SD*=1.8).

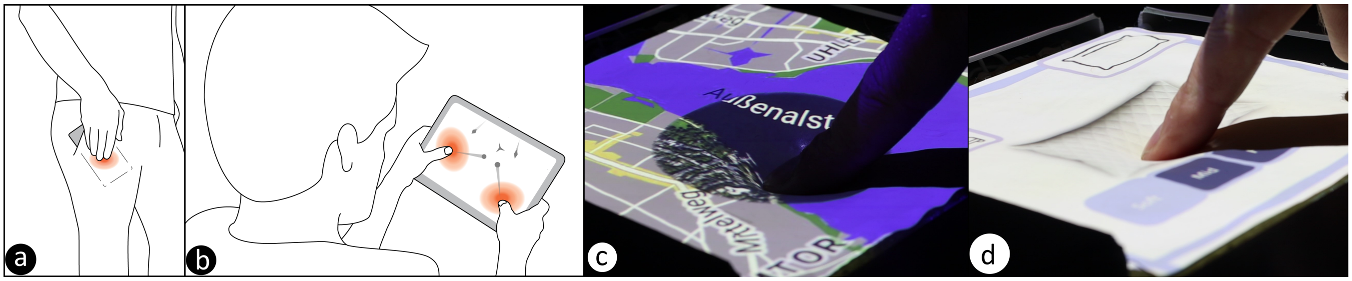


**Figure 5: Conceptual uses cases of DeformIO devices (a) a user pushing into their phone through their trouser pocket to feel information about their taxi arrival time; (b) a user playing a force-augmented game, by applying force to fire projectiles while dodging objects that physically push their fingers out of the display. Implemented applications: (c) The user applies force to a map to create a window into the layer below and; (d) the user can feel the stiffness of a virtual object through DeformIO.**

# 4 VISION FOR DeformIO IN EVERYDAY LIVES

DeformIO enables unique interaction opportunities that are not possible on previous force-augmented displays (Table 1). We present a vision of how DeformIO would integrate deformable force modalities into our everyday activities through a usage scenario of a user traveling to the airport: *(1) Stiffness Augmented Data:* Before leaving for their flight, Taylor uses their DeformIO enabled smartphone to check their destination in a map application. DeformIO allows them to feel topographic or population data encoded into the surface stiffness. By applying force to DeformIO's screen, they can further explore the map by switching between road-map, satellite layers and the terrain of the destination Figure 5c). *(2) Physically Occluded Interaction:* While wearing gloves and with their phone in their trouser pocket, Taylor can check the status of their taxi by feeling the soft surface through their pocket. DeformIO's stiff surface lets them know it's just arriving (Figure 5a). *(3) Force Augmented Games:* On the drive to the airport, Taylor plays a force-augmented game (Figure 5b), applying force with both thumbs to fire projectiles while dodging objects which physically push back against their fingers. The complex force inputs and physical push-back feedback increase the immersion and excitement of the game. *(4) Gaze Free Directions* At the airport, Taylor makes their way through the airport, using the changes in stiffness of their DeformIO watch to guide them to the gate, without having to look at the device. *(5) Online Browsing* After boarding the plane Taylor uses DeformIO to browse online using traditional gestures to swipe between tabs alongside force-augmented gestures to navigate the device. They shop online and can tangibly feel physical objects through their display (Figure 5d).

## 4.1 Implemented Applications

We identified two aspects from our vision for DeformIO, the map and online shopping, and implemented them as stand-alone applications to explore them further. The *Map Navigation application* (Figure 5c) takes advantage of the range of input and output capabilities of the DeformIO, allowing users to carry out traditional gestures (e.g. swiping to pan, pinching to zoom), together with force-augmented interactions. Users can explore the terrain using the stiffness feedback: areas of land are stiff, while areas of water are soft. To change map layers (e.g. from map view to satellite view) the user can apply a force input, creating a window between the layers which increases with the size of the applied force, when they reach the threshold the layer swaps fully and the display stiffens to push the user back and provide tactile feedback.

The *Online Shopping application* addresses one of the key limitations of virtual shopping: the inability of the customer to physically interact with the product. When online shopping with DeformIO, customers can haptically examine and compare the stiffness of various products (Figure 5d). Examples might include understanding the stiffness of sofas, mattresses or pillows, allowing the customer to make more informed decisions before purchase.

# 5 DISCUSSION AND LIMITATIONS

DeformIO is a novel deformable display that integrates force input and variable stiffness output on a single surface. It addresses the challenges of force-shape de-coupling (C1) and dynamic elasticity control (C2) by implementing pneumatic actuation with a novel, asymmetrically elastic silicone structure. However, this design came at a cost of complexity and scalability, as aspects of the fabrication process, proved to be a technically challenging and time-consuming.

Our evaluations identified limitations in the force-sensing accuracy that are likely due to the cell pressure and compression depth altering the physical structure of DeformIO and in turn impacting how forces are transmitted down to the FSR grid. We additionally observed lower than expected perceptions of swiping on DeformIO. In part this can be attributed to participants' comparisons to the highly-refined flat glass interactions surfaces we regularly use, however, it does highlight the challenge of maintaining the ease of fluid finger movements on novel displays.

Our future use scenario demonstrated a range of applications and interactions that could immediately integrate into our everyday lives. However, DeformIO is currently a stationary device, but it must become lightweight, mobile, and robust to deliver our vision. Although this is a significant challenge, researchers have demonstrated several pneumatic devices with some mobility [4, 31]; alternatives include Electro-osmotic Pumps [23] which can provide low-profile, mobile alternatives to pneumatic power.

# 6 CONCLUSION

We presented DeformIO, a novel deformable display that integrates force input and variable stiffness output on a single surface. DeformIO contributes to the field of deformable displays by overcoming the force-shape de-coupling and dynamic elastic control challenges to enable fluid finger movements and co-located force-input and force-output. We evaluated our display through a systematic surface evaluation and a human-participant study, demonstrating the effectiveness of our novel asymmetrically elastic design in detecting force inputs and regulating surface stiffness. We described our vision of how the display can be integrated into everyday life, exploring potential future use cases and developed two demonstrator applications. Overall, DeformIO represents a fundamental step forward in force-augmented devices. It shows how combining deformability, surface continuity and force-input and force-output has the potential to enhance the expressivity and haptic feedback opportunities for interaction in a wide range of contexts.

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