Non-Rigid HCI: A Review of Deformable Interfaces and Input

Alberto Boem *
University of Tsukuba
Virtual Reality Lab, Empowerment Informatics
Tsukuba, Japan
alberto@vrlab.esys.tsukuba.ac.jp

Giovanni Maria Troiano *
Northeastern University
Department of Arts, Media, and Design
Boston, MA, USA
g.troiano@northeastern.edu

ABSTRACT
Deformable interfaces are emerging in HCI and prototypes show potential for non-rigid interactions. Previous reviews looked at deformation as a material property of shape-changing interfaces and concentrated on output. As such, deformable input was under-discussed. We distinguish deformable from shape-changing interfaces to concentrate on input. We survey 131 papers on deformable interfaces and review their key design elements (e.g., shape, material) based on how they support input. Our survey shows that deformable input was often used to augment or replace rigid input, particularly on elastic and flexible displays. However, when shapes and materials guide interactions, deformable input was used to explore new HCI paradigms, where gestures are potentially endless, and input become analogy to sculpting, metaphor to non-verbal communication, and expressive controls are enhanced. Our review provides designers and practitioners with a baseline for designing deformable interfaces and input methodically. We conclude by highlighting under-explored areas and identify research goals to tackle in future work with deformable interfaces.

Author Keywords
Deformable interfaces; input; shape-changing interfaces, non-rigid interactions; organic displays; bendable displays; flexible interfaces; sensing; mapping; shape; material

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

INTRODUCTION
Research in HCI is shifting focus from rigid to non-rigid interactions [60, 29], and the use of non-rigid materials for interactive applications (e.g., music, gaming) is constantly under investigation [172, 173, 83, 166, 133, 142, 135]. Several prototypes exist that show potential applications for non-rigid interactions, including elastic and flexible displays that are bendable and stretchable [163, 189, 65, 1, 146, 101, 3, 79, 134, 92, 19], deformable controllers for gaming [122, 156, 102], jamming user interfaces [62, 42], and deformable interfaces for music performances [16, 196, 173, 157, 169, 70, 106].

*The authors contributed equally to this manuscript

DIS'19, June 23–28, 2019, San Diego, CA, USA

DOI: https://doi.org/10.1145/3322276.3322347

However, the term *deformable* is often blurred with the term *shape change* [83, 166], or used to describe material properties of shape-changing interfaces [133, 166, 135]. Consequently, as shape change emphasizes output and self-actuation [135, 136, 4], earlier work exclude deformable interfaces that are input-only [166] (e.g., BendID [122]), and under-discuss input [133, 135]. Therefore, we lack overviews of deformable input and its use for interactive applications. To compensate for that, we (1) distinguish deformable from shape-changing interfaces and (2) develop a review of non-rigid interfaces, specifically deformable interfaces, which is angled towards input.

We define *deformable interfaces* those that (1) are entirely or in part made of soft and malleable materials (e.g., rubber), (2) require physical input to be deformed, and (3) allow users to input in ways that are unlikely (if not impossible) with rigid interfaces (e.g., bend, stretch [178]). As such, we do not consider interfaces where users input by re-configuring rigid materials [75, 126, 34, 44, 57, 140], and that do not allow for direct, physical input on the interface [100, 99, 182]. We survey the state-of-the-art in designing deformable interfaces and input by reviewing 131 papers from various research communities (e.g., CHI, NIME, DIS, TEI, UIST). We use grounded theory [48] to analyze the deformable interfaces presented in the 131 papers and identify five elements that form the basis of their design, namely (1) shape, (2) material, (3) input sensing, (4) I/O mapping, and (5) use of deformable input.

With the present survey, we aim to generate an extensive overview of existing deformable interfaces that shows (1) how such interfaces are designed, (2) what are the basic elements that constitute their design, and (3) how is deformable input designed and for what interactive applications. For designers and practitioners, the review represents a baseline from which inspire the design of future deformable interfaces and approach design practices more methodically. For researchers, the review defines *deformable* interfaces, discusses open research questions, and provides a list of research goals for future work.

SCOPE AND MOTIVATION
Recently, research on HCI has seen the emergence of various papers that review non-rigid interfaces from different perspectives, including a survey of the design space and research challenges of shape-changing interfaces [135, 4], a review of

shape-changing interfaces for design and application-based research [166], and reviews of materials and objects that have shape-changing properties [133, 83]. However, the aforementioned reviews emphasize the output characteristics of non-rigid interfaces (e.g., self-actuation), and widely discuss shape *resolution* [142, 83], *orientation* [135], and *actuation* [133], while deformable input and its design are seldom discussed. Furthermore, to reinforce the focus on output, previous review exclude non-display and input-only interfaces [166]; for instance, deformable interfaces for music [109] and gaming [156] are not considered.

We focus on input and include non-display and input-only interfaces. As such, we integrate previous work by reviewing deformable input more extensively and show (1) how deformable interfaces are designed for input, (2) what are the characteristics of deformable input, (3) how is deformable input designed for interactive applications, and (4) reflect on how deformable interfaces and input redefine HCI paradigms. Additionally, we found that the way researchers described interfaces as *deformable* in earlier reviews is ill-defined and may lead to ambiguous interpretations. For instance, Sturdee et al. described input with Paddle [134] as allowing for *"user-controlled deformations*". However, Paddle uses rigid surfaces for input, which may be re-configurable [83], but are not "deformable", for instance as in ShapePhone [43], where the interface can be physically stretched or bent because made of malleable material. As such, we felt the need to disambiguate between the terms *deformable* and *shape change*, and define deformable interfaces as its own sub-field of non-rigid interfaces.

DEFINING DEFORMABLE INTERFACES

Previous review describe interfaces that can deform and shape change through the term *shape-changing* interfaces. However, they require interfaces to be self-actuated [135, 4], emphasize output [142, 133, 4], and exclude non-display or input-only interfaces [166]. We emphasize input and user-controlled deformation and see deformable interfaces as:

1. Made entirely [132] or in part [38] of soft and malleable materials, including fabric, rubber, and clay.
2. Emphasizing physical input and user-controlled deformations over self-actuation and shape change [135],
3. Supporting user input through deformable materials, even when combining rigid and deformable parts (e.g., [181, 119]), or when actuated (e.g., [68, 85, 143]),
4. Allowing users to input with gestures that are unlikely or impossible with rigid interfaces (e.g., *twist* [59], *bend* [47]).

METHOD

We searched for papers from HCI proceedings (e.g., CHI, TEI, UIST), music proceedings (e.g., NIME, ICMC), and browsed several online libraries (e.g., ACM, IEEE, Springer, Elsevier), to cover the most relevant areas. We filtered our search using the keywords "deformable", "malleable", "elastic", "flexible", "bendable" "organic", "shape-changing", "soft tangible" AND "interface" OR "display", and collected a total of 149 papers. The complete list of papers included in our review can be found at www.deformableUI.com. We applied the definition of *deformable interfaces* to the collected 149 papers and found that 18 did not match the criteria. We reviewed the selected 131 papers and analyzed deformable interfaces based on grounded theory [48], in particular content analysis [164] and affinity diagramming [174, 52, 13]. We conducted the analysis verbally over several meetings, using Excel sheets and Google Docs for annotating the discussions, and RealTime Board[1] for affinity diagramming. After three months, we reached consensus on the five elements that form the basis of designing deformable interfaces: (1) shape, (2) material, (3) input sensing, (4) I/O mapping, and (5) use of deformable input. Next, we first describe deformable input and its characteristics. Then, we outline the first four design elements listed above and show how they are designed to support deformable input and for what interactive applications. We conclude by explaining how deformable input is used to augment and replace earlier HCI paradigms (i.e., rigid multi-touch input), or explore new ones.

DEFORMABLE INPUT

Interacting with deformable interfaces requires physical manipulation of shapes and materials. Users can input on deformable interfaces by using their hands e.g., [172]) or the entire body (e.g., [128]). Deformable interfaces add depth to bi-dimensional touch input (e.g., [172, 24, 189]), allow users to deform interfaces by means of stretch [180], bend [38], twist [80], squeeze [178], and combine those to allow for multidimensional input (i.e., multiple deformations used simultaneously for controlling various parameters [59]). Furthermore, as deformable interfaces are made of soft and malleable materials, they may afford energetic and aggressive input like slapping [120] and punching [91].

Hand-Based Deformable Input

Deformable interfaces allow for one- or two-handed input, with bend, squeeze, stretch, twist, and push being most common. Bend is used frequently in deformable displays and controllers [47, 35, 37, 185, 59, 79, 5, 122, 157, 155, 67, 96, 5, 102, 96, 92], and users generally like corner bend as a gesture [185, 35]. One-handed squeeze is widely used as input for controllers and music interfaces [51, 12, 191, 192, 173, 45]. Stretch is less common compared to bend and squeeze, and can be two-handed [180, 194, 139, 16, 203], or one-handed [25, 167, 202]. Twist is the result of bending with two hands in opposite directions and can be performed either vertically [87, 118] or horizontally [110, 80, 79, 81]. Push is used often for input on elastic displays for depth-touch [189, 24, 68, 129, 72, 172, 55].

Other hand-based deformable input include twiddle [149], punch [91], slap [120], prod [106], roll [124], and shear [190]. Although becoming common in HCI, previous work showed that creating a vocabulary for hand-based deformable input is hard [172], as users still tend to rely on earlier paradigms based on rigid input (e.g., multi-touch), particularly when deformable interfaces resemble rigid displays or tasks are inspired by touch and WIMP interactions.

[1] https://realtimeboard.com/

Body-Based Deformable Input
Body-based input for deformable interfaces is uncommon. However, there are few examples. BendableSound [28] allows for input with hands but encourages its users to input with other parts of the body too, such as the head or the arms. FuwaFuwa [168] and Ballagumi [106] allow for input with the mouth and the neck. SmartSleeve [128] is a deformable interface worn on the arm that can be bent for input by flexing the forearm. Emoballoon [120] can be hugged and squeezed to the chest for cuddling interactions. However body-based input with deformable interfaces remains under-explored, because, at this stage, deformable interfaces are still designed to fit dominant HCI paradigms [18].

Kinetic Deformable Input
As said above, deformable interfaces can afford aggressive interactions and input due to their softness and malleability. For instance, when Emobaloon [120] is slapped it will flash a red light and interpret the user input as "aggressive". Inflated Roly Poly [91] lets users punch and poke the display to blow up bubbles in virtual games. However, as body-based deformable input, kinetic input with deformable interfaces are also under-explored.

Multidimensional Deformable Input
Deformable interfaces may allow for multidimensional input, where each deformable input can be used to control an individual output [122]. There are few examples of deformable interfaces that allow for two simultaneous input. Examples include twist + touch [80], bend + touch [5, 19, 35, 36], and stretch + touch [180], which combine rigid and deformable input. There are also examples where two simultaneous deformable inputs are allowed, including bend + twist [80, 158, 157, 59, 156], twist + stretch [25, 16, 195, 77, 53], and bend + push [122]. At present, multidimensional input with deformable interfaces are being explored. In particular, research about conductive polymers [49] and nanomaterials [84] shows promise for deformable input beyond two dimensions [144]. However, sensing more than two deformations simultaneously remains challenging. Despite technical feasibility, there are still no research that explore the extent to which users can handle multiple deformations for input, and what are the benefits.

SHAPE
This section presents an overview shapes used with deformable interfaces (Figure 2). We considered shapes of deformable interfaces before user manipulation and found two main types of shape: (1) *volumetric* and (2) *flat*. Flat shapes are widely used for interfaces that act like deformable displays, while volumetric shapes follow applications and interactions.

Volumetric
Volumetric deformable interfaces are 3D-mensional and 2.D-dimensional, and can be either *geometric* (e.g., cube, sphere), or *organic* (e.g., zoomorphic, xenomorphic).

Geometric
Geometric deformable interfaces have the shape of geometric primitives. We identified four types of geometric shapes: (1) *spheroid*, (2) *cuboid*, (3) *cylindric*, and (4) *tetrahedron*.

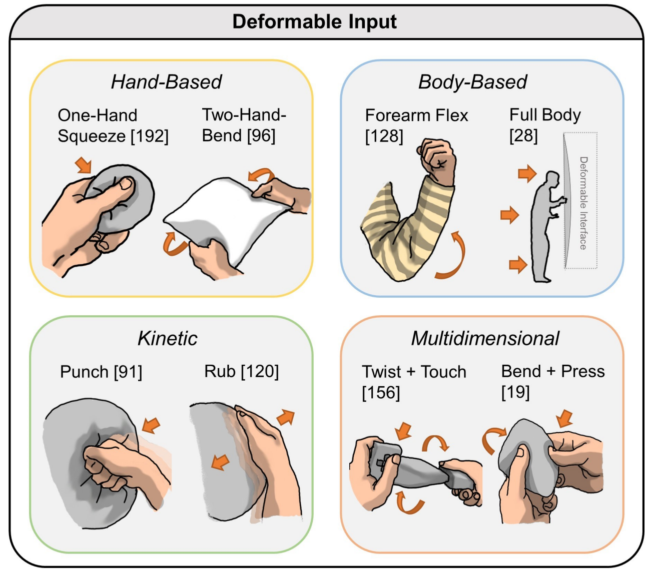

Figure 1: Characteristics of deformable input; © Troiano & Boem

Spheroid are sphere or hemispherical. Spheres were used to create deformable interfaces for music [173, 58, 191, 70, 193], virtual 3D sculpting [159], and soft lamps [179]. Emoballoon [120] used rubber balloons to create deformable interfaces that infer user intentions based on the character of deformable input (e.g., hug-is-friendly). Bacim et al. [7, 6] used hemispherical, elastic displays to investigate multi-touch on curved surfaces. OrbTouch [93] allowed users to move Tetris pieces by deforming a soft hemispherical controller. DeformWear [190] is a soft hemispherical controller that is worn on the index finger ad controlled via the thumb for navigating maps or playing video-games on external displays and VR headsets.

Cuboid can be shaped like cubes or rectangles. As spheroid, they were used as deformable interfaces for music [173, 17, 77, 87] and virtual 3D sculpting [117, 155]. MARSUI [197] and Soundflex [169] coupled deformation with auditory feedback on malleable rectangular interfaces; the user deforms the interface guided by sounds to put it in specific modes (e.g., folded around the wrist is "watch" mode). BendID [122] and TWEND [59] used rectangular soft interfaces to support multidimensional bend + twist input for gaming and mobile applications. Kildal et al. investigated bend + twist using similar prototypes [78, 79]. ShapePhone [43] proposed prototypes of deformable, shape-retaining smartphones, which are stretched to morph into TV remote or Wiimote-like controllers.

Cylindric shapes resemble cylinders or tubes. HandLog [12] used soft cylinders to support squeeze input for gaming. Watanabe et al. [187] used flexible rubber cylinders to explore deformable input on rigid mobiles, such as finger-flicking to ignore e-mails, or twisting to scroll emoji menus. SonicBanana [157] used tube-shaped flexible interfaces as MIDI controllers that users can bend or twist to perform music. Sculpton [16] used tetrahedron shapes to create malleable music interfaces for "sculpting" sounds with the hands.

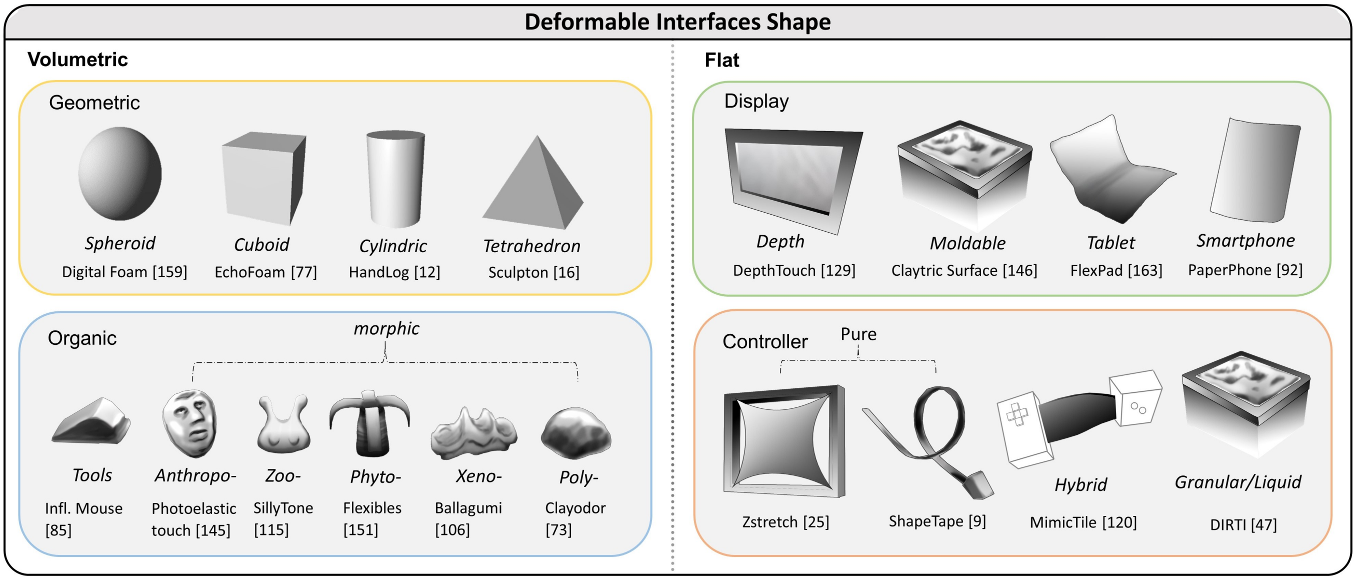

Figure 2: Types of shapes for deformable interfaces; © Troiano & Boem

Organic

Organic deformable interfaces can be shaped after tools, real life objects (e.g., plants), or be arbitrary. We found six types of organic shapes: (1) *tools*, (2) *anthropomorphic*, (3) *zoomorphic*, (4) *phytomorphic*, (5) *xenomorphic*, and (6) *polymorphic*.

Deformable interfaces shaped like tools include Inflatable Mouse [85] and FlexStylus [39], which add deformable input to computer mice and rigid stylus for WIMP and drawing applications. Anthropomorphic and zoomorphic deformable interfaces resemble human and animal shapes. Sato et al. [145] used transparent rubber on multi-touch tabletops to create a humanoid face that changes facial expressions when poked or squeezed. SillyTone [115] is a rabbit-shaped, deformable interface that plays sounds when its ears are bent or squeezed. Flexibles [151] are shaped like trees and users can bend and release them fast to throw fruits at each other in AR games.

Xenomorphic shapes look organic but are unusual and strange. Examples are Ballagumi [106], Glume [127], and Senspectra [94], which allow for deformable input respectively for music, creating network platforms for 3D modeling, or sensing mechanical strain. Finally, polymorphic interfaces can be deformed by users to any desired shape. We found many example of clay-based, polymorphic interfaces, which were used for various applications and domains, including music [188], real-time model-capturing for AR [138], odor retrieval [73], gaming [184], and education [14, 199, 150]; input with such interfaces follow dynamic affordances of highly deformable materials and gestures become potentially endless.

Flat

Flat deformable interfaces (Figure 2) have a two-dimensional shape and are either display or controller. Deformable displays have co-located input and visual output on the very same surface. Designers of such deformable interfaces often explicitly reference existing multi-touch technology as a source of inspiration (e.g., [129]). Deformable controllers are input-only interfaces, where input and output are not co-located.

Displays

Deformable displays resemble rigid multi-touch displays (e.g., touchscreens, smartphones). On deformable displays, deformable input augments or replaces multi-touch. They provide visual output, unless used as proof-of-concept prototypes [96]. Deformable interfaces that resemble displays often have elastic surfaces, which allow for depth-touch along with bidimensional multi-touch input [129, 189], and may support deformable gestures [174]. Examples include Khronos Projector [24], a pushable display for interactively explore videos and pictures in four dimensions.

The Deformable Workspace [189] and DepthTouch [129], are elastic displays for depth multi-touch and 3D sculpting applications. BendableSound [28] is a wall-sized elastic display that helps autistic children develop motor skills through expressive therapies. Troiano et al. [172] used a guessability method [198] to investigate user-defined gestures for elastic displays, showing that users input with deformable gestures mostly when tasks involve manipulating and displacing 3D objects.

Deformable displays can be shaped after rigid tablets and smartphones. Bend input was widely used on prototypes of flexible tables and smartphones [185, 30, 96, 97, 5]. Bendy [102] and Flexpad [163] used deformable input on flexible tables for mobile gaming and controlling video-animations. Flexible smartphones were used to investigate bend input for various mobile applications [37, 47, 92, 20], including password creation [108], map navigation and browsing [152, 3, 19, 47, 45, 81], music [50], holographic gaming [51], nonverbal communication [165], and blind interactions [35, 37]. Moldable displays can be deformed by users to desired shapes [112], varied in stiffness [125], be wrapped around rigid objects [101], and can self-actuate to provide haptic feedback [68]; such displays are flat at their default state (i.e., before users manipulate them). Tunable Clay [43] and Claytric Surface [146] provide users with variable stiffness displays that can be deformed and made hard to "lock" the created shapes. IlluminatingClay [131] and Sandscape [62] allow users to deform malleable displays to explore the topography of visually-augmented physical landscapes; Phoxel-Space [137] proposed similar displays but for medical applications.

DeforMe [132] and deForm [42] propose gel-based displays for creative 3D modeling and picture distortion, where users input with their hands as well as arbitrary objects (e.g., toys), and fiducial markers [71]. Lepinski and Vertegaal use fabric to create displays that can conform to the shape of rigid objects and be visually-augmented for organic-feel, desktop interactions [101]. MudPad [68], Tablehop [143], and Feelex [64] are displays that are both deformable and shape change to provide users with haptic feedback via mechanical and fluid actuation.

Controllers

Flat deformable interfaces were proposed as controllers for various applications. Controllers with flat, elastic surfaces were proposed for music [123, 173, 25], and sonification-based data exploration [113]. Trampoline [55] uses elastic surfaces, which can be pushed from both the front and back sides, to input in virtual repoussé and chasing applications. ElaScreen [204] is a pushable touch-pad for depth-navigating datasets through their graphic visualizations. Elasticcon [88] uses elastic strings for eyes-free input when browsing content on interactive glasses or external displays. *Flexible* strips like ShapeTape [9], RoCuModel [154], and fStrip [27]. were used as input interfaces to model NURBS or for non-verbal, symbol-based communication. PerForm [196] uses flexible frames as music interfaces, which can be reshaped by users to play different musical sounds (e.g., tambourine, guitar).

FlexSense [139] uses thin plastic sheets placed on rigid tablets to augment rigid input with deformable input. Follmer et al. [43] combined deformable input and haptic feedback with pneumatically-actuated, transparent flexible controllers for tactile exploration of pictures and maps. Flexy [177] allows users to control digital animations via flexible interfaces loaded with conductive ink. Other deformable controllers augment rigid interfaces [180, 203, 202] or human body parts [128, 201], with flexible materials that allow for input. Examples include PaperNinja [38] and MimicTile [119], which augment rigid input on smartphones with flexible parts for bend input. Bentroller [156] combines bend and twist input with rigid input on a Nintendo®-like deformable game-pad. Finally, DIRTI [147] and Linetic [90] are controllers made of sand or fluids, and can be dynamically reshaped by users.

MATERIAL

Various materials were used with deformable interfaces, including, fabrics [129], rubbers [145], and composites [169]. We discussed materials based on studies of material science [22] and haptic perception [95, 89, 10, 32]. We found that deformable materials could be characterized as: (1) *non-shape-retaining* and (2) *shape-retaining* (Figure 3).

Non-Shape-Retaining

Non-shape-retaining materials reverse to the original shape when removing external force. Based on elasticity and reverse speed, they can be: (1) *elastic*, (2) *flexible*, or (3) *malleable*.

Elastic materials are favorable for deformable input like stretch and push, and will spring back to their original shape fast. They include fabrics (e.g., cloth [129, 25], elastane [172, 55, 201], yarn [180, 167, 124]), and rubbers (e.g., silicone, [145, 113], latex [120, 7], PVC [91]). Designers of deformable interfaces attached thin sheets of fabric or rubber to rigid frames, and tense them to create elastic surfaces [55, 204, 189, 93, 181, 113, 7], which users can pull, stretch, and push to input [172]. Khronos Projector [24], The Deformable Workspace [189], DepthTouch [129], Zstretch [25], SilentDrum [123], and BendableSound [28], were created in such way. Troiano et al. [172] showed that users enjoy input on elastane due to low friction when in contact with the skin, but that it is hard to grab and pull because slippery. Kingsley showed that input supported by elastic fabric is more accurate than mid-air, but surface tension makes it hard to input at the corners [86].

Flexible materials are stiffer than elastic and afford well deformable input like bend and twist [59, 173]. Flexible plastic sheets were used as proof-of-concept prototypes to explore bend and twist for mobile applications [185, 59, 139, 30, 108, 102, 96, 152, 79, 81, 97, 200]. Gallant et al. [45] used paper prototypes for similar research, while Ernst et al. used stiff cardboard [36] and flexible silicone [35, 37] to investigate bend input for blind interactions; they showed that users like corner bend and enjoy the tactile feedback of silicone. Girouard et al. [47] augmented silicone with above-projection and investigated one-handed bend, showing how deformable input can compensate for issues of rigid mobile (e.g., unreachable targets and grip re-adjustments). E Ink-based flexible displays [92, 19], OLED displays attached to plastic boards [3], and Flexible OLED (FOLED) [50, 20, 33], were used to create high-quality prototypes of deformable smartphones.

Malleable materials are softer than flexible and support well squeeze and push. Foam-based interfaces were covered in fabrics to provide users with smooth tactile experiences [109, 110, 173, 70, 87, 193, 53, 178] and used to explore squeeze for music interactions [17, 77, 173, 87, 70, 53, 205, 193, 109, 110], making virtual 3D sculpting physical [117, 155, 159], and explore expressive input for gaming [12, 122, 156]. Silicone, latex, and gels were used for creating malleable music interfaces [16, 191, 58, 106], while fluid metals or gels covered in fabric or thin film, were used as malleable displays and widgets [90, 103, 68, 42]. SmartSleeve and FabricKeyboard use fabric to create soft surfaces for deformable input on the forearm [128], or MIDI keyboards that can be stretched and pulled for playing music [195].

Shape-Retaining

Shape-retaining materials are capable of maintaining user-created shapes when external force is removed. Also, they can vary in stiffness to physically match digital contents [125], or create intersections between rigid and deformable interactions [146]. Shape-retaining materials can achieve shape-retention either (1) *naturally*, (2) *mechanically*, or (3) *computationally*.

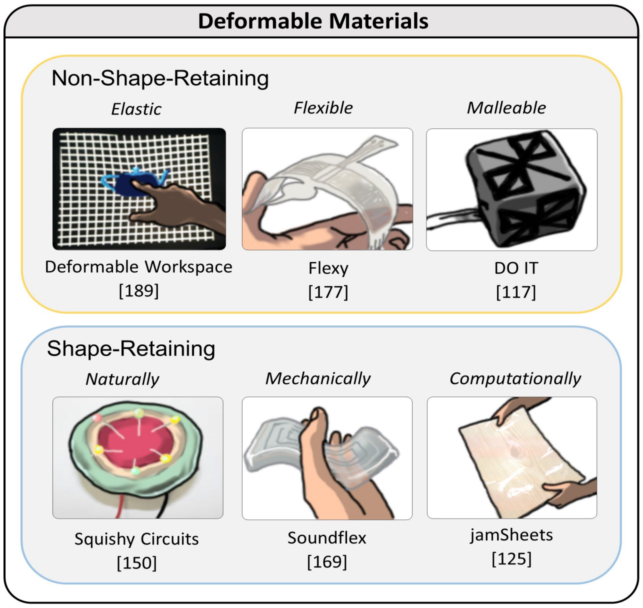

Figure 3: Deformable materials; © Troiano & Boem

Clay and paper are naturally shape-retaining; such materials may bring deformable input beyond gestures to enhance interactions that follow material properties. Squishy Circuits [150] were used to introduce kids to electronics through creative play with conductive dough. PIPLEX [14] allows kids to control virtual characters and manipulate objects in AR educational games using plasticine. ClayTone [188] allows users to create "sound sculptures" using clay. Reed [138] proposes digitally augmented clay, which shape can be tracked and computationally reconstructed as users deform it. DeForMe [132] and Phoxel-Space [137] use clay to create deformable displays that allow users to physically deform digital contents. Clayodor [73] lets users deform clay into fruit shapes (e.g., a banana) to retrieve odors.

Apart from clay, Projectagami [170] uses paper to demonstrate deformable displays that can be shaped after applications, such as flat for map navigation or folded for online shopping. Sandscape [62] and DIRTI [147] use several small glass beads to create deformable interfaces that retain shapes through spatial conformation [135, 174]. Soft materials can mechanically retain shape when combined with stiffer ones. Iron wires embedded into silicone, foam, and plastic allow deformable interfaces like MARSUI [197], SoundFlex [169], Flexpad [163], and fStrip [27] to retain shapes while remaining flexible. In Illuminating Clay [131], iron wires and clay were combined to create deformable displays that allow for both natural and mechanical shape-retain. Mechanically shape-retaining materials seem to be favorable for accurate and gesture-based deformable input. Computationally shape-retaining materials can vary stiffness through computer-controlled mechanisms. Claytric Surface [146], Tunable Clay, and ShapePhone [43], use particle jamming to create deformable, shape-retaining interfaces, where soft particles (e.g., coffee grounds), covered in fabrics or thin sheets of latex, vary stiffness through computer-controlled solenoid valves. jamSheets [125] uses air suction for layer jamming and variable stiffness without using jamming particles. Volflex uses computer-controlled air cylinders [65] for shape-retaining. MimicTile [119] uses shape-memory alloys (SMA) for variable stiffness edge input on smartphones.

INPUT SENSING

Sensors make deformable materials interactive and allow input to be recognized through sensing techniques. Choices of sensors and sensing techniques are based on (1) the deformable input that needs to be sensed, (2) physical characteristics of interfaces (e.g., shape, size, deformability), and (3) interactive applications. We reviewed sensing for deformable interfaces based on the categorization of *non-perceptual input* proposed by Karam and Schraefel [74], and found two main approaches to sensing: (1) *embedded sensing* and (2) *external sensing*.

Embedded Sensing

Embedded sensing relies on sensors that are embedded in deformable materials. The majority of deformable interfaces included in our review used low-cost, commercially available sensors for embedded sensing. Low-cost flex sensors [67, 59, 152, 200, 92, 185, 102, 157, 205, 70, 197, 173, 87, 50, 35, 5, 51, 125, 38, 19, 108, 47, 171, 30, 196], and strain gauges [9, 79, 25, 81, 20, 27, 3, 82], were used to sense bend and twist, while force sensitive resistors (FSR) were used for press and squeeze [70, 109, 67, 200, 115, 58, 193, 191, 5, 125, 73]. For sensing stretch, Troiano et al. [173] and Chang et al. [25] used conductive rubber chords embedded in elastic fabrics, while others woven conductive thread into fabrics or paper, which approach can be used to sense stretch and bend on both flat [128, 180, 8] and volumetric surfaces [53, 191].

Designers of deformable interfaces strategically placed sensors in specific configurations for unobtrusiveness, sensing input in multiple areas, or enable gesture-based input. Flex sensors and conductive tapes [169, 197] were placed inside [173, 157] or on the back [205, 156, 185, 30, 108] of prototypical deformable interfaces to hide sensors from users. MARSUI [197] places conductive tape inside silicone to create sensors layout that sense bend independently in multiple areas (e.g., at center and corners). Masqood et al. [108] strategically placed flex sensors only at the corners of a silicone smartphone prototype to sense corner bend. The aforementioned examples show how designers can take advantage of commercial sensors to sense deformable input. However, embedding low-cost, commercial sensors in deformable materials presents limitations. First, they wear out fast and may require creative escamotage to be fit to custom shapes (e.g., [157]). Second, depending on sensors' size and thickness, the stiffness and weight of materials may increase, thus affecting interface robustness and control experience. Hence, designers explored alternatives to increase robustness and resistance of deformable interfaces. For instance, fiber optics and photo-reflective sensors were used instead of flex sensors to sense bend and twist [9, 39, 154, 26, 16], but also for stretch and squeeze [17, 190, 167, 168, 16]. I/O Braid [124] used a combination of fiber-optics and conductive yarn to sense several gestures, such as pinch, roll, and grab. Trampoline [55] used a combination of magnets and hall-effect sensors to allow for deformable input on elastic fabric, without burdening the very input surface. Others used conductive materials, including conductive fabric [195], conductive foam [117, 159, 12, 121, 121], conductive 3D-printed materials [151], conductive dough [150, 199], electro-active polymers (EAP) [122], and conductive ink [177]. Particularly interesting are sensing approaches that use conductive materials stacked in layers to sense multiple deformations. BendID [122] used a grid made of nine EAPs sandwiched between two layers of conductive foam covered in conductive fabric, to sense bend and squeeze simultaneously and at different locations. FabricKeyboard [195] used layers of interwoven conductive fabrics to sense touch and stretch as input for controlling sounds. In MultiSoft [203] and iSoft [202], Yoon et al. explored Electrical Impedance Tomography (EIT) as a technique to create elastic surfaces, that can discriminate between different inputs, including multi-touch and stretch.

External Sensing

External sensing relies on sensors that are placed outside deformable interfaces. The deformable interfaces included in our review use external sensing based on computer vision (e.g., blob detection) via image sensors (e.g., CCD). External sensing tends to emphasize how a shape or a surface is deformed, rather than sensing specific gestures (e.g., [163]). Compared to embedded sensing, external sensing has the advantage of not burdening deformable materials and may offer better sensing resolution. However, with external sensing deformable interfaces are bound to the capture areas of image sensors (e.g., [163]). Also, the approach can be economically and computationally expensive, it may require specific light conditions (e.g., darkness), and portability can be an issue.

Single charge-couple device (CCD) sensors were widely used for sensing deformable input [181, 113, 188, 123, 31, 155, 45, 189, 184, 72, 145, 137, 101, 24], but stereoscopic CCD sensors were used too [101]. Cassinelli et al. developed a custom image sensors that combines CCD and infra-red (IR) to sense depth input on elastic displays [24]. IR sensors alone were used to detect input on deformable displays [43, 7, 6, 189, 132, 137, 21, 42, 62]. A combination of invisible markers and IR sensors was used to interpret and sense shape deformation on deformable displays like DeForMe [132] and InformationSense [21]; similar results were obtained using polarized filters [145], and extraction of features like the contour of interfaces' shape [188, 184, 123], or their color [188, 184, 31]. Recently, the use of depth sensors like the Microsoft Kinect® has slowly replaced IR technology for sensing deformable input [162, 28, 170, 21]. Also, depth sensors can capture deformations in high-detail and do not require added markers for surface tracking or for reconstructing the geometry of shapes deformed by users [163, 21]. Finally, hybrid embedded/external approaches to sensing are also possible. jamSheets [125] combined image sensors with flex sensors for enabling deformable input and adapting projected visual contents to user-deformed surfaces in real-time. Through algorithmic interpretation and filtering of sensors' signals, gesture-based interactions via deformable input are possible.

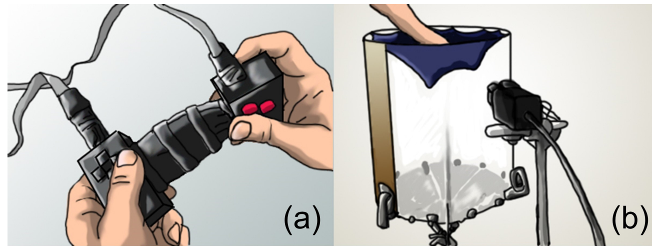

Figure 4: Two examples of input sensing: (a) Bendtroller [156], sensing input through embedded flex sensors; (b) SilentDrum [123], sensing input via CCD sensor; © Troiano & Boem

Recognition and Classification of Deformable Gestures

Deformable input inherently involves performing gestures (e.g., squeeze), but not all deformable interfaces are designed with gestures in mind (e.g., [24]). Previous work designed deformable input based either on sensors' characteristics, or on how shapes and materials deform and used those deformations to infer gestures (e.g., [43, 62, 188]). Here we report recognition and classification techniques used to design gesture interactions with deformable interfaces. There are two main approaches to gesture recognition and classification: (1) *feature-extraction* and (2) *machine learning*.

Feature extraction approaches gesture recognition by relying on individual sensors for individual gestures (e.g., flex sensor –> bend [173]), on individual sensors to extract multiple features (e.g., magnitude and direction [20, 3]), or by placing sensors in particular configurations to extract features from combined sensors values (e.g., [156]). Warren et al. [185] extract location, direction, size, angle, speed, and duration of bend using six flex sensors and signal thresholding. Daliri et al. [30] use similar approaches to recognize 12 bend gestures (e.g., up, down, left, right). Shorey et al. [156] use two flex sensors arranged in a cross-like pattern and recognize bend and twist by thresholding combined sensor values.

Zadel et al. [205] recognize up-down bend by measuring positive and negative curvature of four pairs of flex sensors. Marier uses two three-axis accelerometers to recognize bend and twist by differentiating their pitch and roll [109, 110], while Boem uses six optical sensors and recognize stretch and bend by thresholding the combined sensor values [16]. In sum, feature-extraction is convenient when sensors' signal need simple filtering and gestures can be recognized straightforwardly.

However, contingent on design choices and needs, recognizing and classifying gestures based on deformable input may be challenging. In such cases, previous work used pattern recognition and machine learning. PaperPhone [92] used k-Nearest Neighbour (k-NN) to recognize and classify bend gestures based on features like orthogonality, consistency, polymorphism, and directionality of bend. BendID [122] and MultiSoft [203] used support vector machines (SVM) to classify and discriminate between deformable gestures (e.g., the direction of bend, position, and intensity of push).

Emoballoon [120] used SVM to measure intensity and character of deformable input, and based on rapidity and strength of kinetic input interpret users' intentions (e.g., gentle-squeeze-is-friendly, violent-rapid-push-is-aggressive). The Skweezee System [178] could recognize up to seven user-defined gestures on soft cubes and cylinders via SVM. Smart Sleeve [128] used SVM to recognize and classify several deformable gestures performed by users on smart fabrics placed on the forearm. Besides SVM, Artificial neural network (ANN) was also used to recognize and classify gestures with deformable interfaces [149, 169]. For instance, Larson et al. [93] used convolutional neural networks (CNN) to predict deformable gestures, by extracting spatiotemporal features from recorded user input on deformable surfaces.

I/O MAPPING

One characteristic of deformable interfaces is the capacity of being both generic and specific [173]. This is contingent on how deformable input is mapped to the output and for what applications. Thus, mapping strategies vary heterogeneously, as deformable interfaces can fit a wide variety of applications. However, they are seldom documented. We review I/O mapping with deformable interfaces following earlier work on digital music instruments (DMIs), which has a long tradition on systematic investigations of mapping [107, 69, 114]. We found that deformable input was mapped to output based on either (1) *explicit mapping* or (2) *implicit mapping*.

With explicit mapping, the input corresponds directly to the output. For instance, in ClayStation [184] and Flexpad [163], the shapes of deformable interfaces are equal to their digital counterparts, and the effects of deformable input are directly matched by and visible in the output. As such, explicit mapping can be used to create physical consistency between the deformable interface and the contents that they manipulate. This is favorable for virtual 3D sculpting and modeling applications [117, 155, 9, 154, 55]. Explicit mapping with deformable music interfaces is harder, as sounds are abstract and their relationships to deformable input requires analogies [109, 110, 16, 123, 157]. However, previous work showed that musicians find squeeze and stretch related to volume and pitch [173]. Interestingly, the study shows that for musicians, stretching an elastic surface is directly related to "stretching" the pitch of sounds (e.g., [25]), while expanding volume loudness is inversely related to squeezing a malleable interface [173]. However, explicit relationship between input and output with deformable interfaces should be further investigated.

With implicit mapping the correspondence between input and output is based on analogies and metaphors. Differently from explicit mapping, the input is not physically consistent with the output (e.g., input shape = output shape [9, 163]), but rather mapped to functionality and actions that are represented by deformations. For instance, the up/down direction of bend was mapped to zooming on maps [5, 45, 152], items selection [152, 98], and mobile locking [5]. Implicit mapping was used to create analogies between bend and twist and the speed of objects in video games [122, 156], between twist and audio effects (e.g., distortion) in music [173], and between squeeze and speed of zooming [85, 45, 19]. Stretch was mapped to control

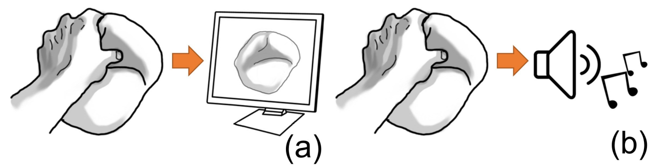

Figure 5: Deformable I/O mapping. (a) ***explicit*** **- physical manipulation corresponds to its digital counterpart [117]; (b)** ***implicit*** **- deformable input is analogy to sound [173];**

time-based events, such as the playback speed of videos [31] and sampled sounds [188, 25]. In Khronos Projector [24] the simple action of pushing into a deformable display becomes metaphor to exploring the fourth dimension of videos and pictures. Often, deformable interfaces using implicit mapping regarded control as expressive [58, 110, 173].

Although implicit mapping shows interesting possibilities for deformable input that are based on the use of metaphors and analogies, examples are still sparse and we need a more systematic understanding of I/O relations. A better understanding of I/O relations may help better design the use of deformable input for interactive applications. Next, we show how deformable input was used for interactive applications, and retrospectively analyze how it moves HCI from earlier paradigms to newer forms of input interaction.

USE OF DEFORMABLE INPUT

We see three uses of deformable input, which move gradually from hybrid rigid/non-rigid, to fully non-rigid interactive applications and paradigms: (1) *deformable input augments rigid input*, (2) *deformable input replaces rigid input*, and (3) *deformable input follows shapes and materials*.

Deformable Input Augments Rigid Input

Deformable input was used to augment rigid input in different ways, for instance by combining flexible parts with rigid ones [180, 85, 187, 39, 38, 119], or by using rigid input (e.g., multi-touch) on deformable interfaces (e.g., [129]). Examples include Cobra [200] and Behind-the-Tablet Jamming [43], where rigid multi-touch tablets allow for flexible input on the back, or FlexStylus [39] where users control the size of digital brushes in drawing applications by bending the flexible parts of rigid stylus.

Others implemented multi-touch gestures on elastic displays [129, 189, 6, 7], such as rotating digital objects with two fingers [189]. The aforementioned examples explored how rigid and deformable input can coexist on the same interface, and be either (1) assigned to different functionality for integrated control performances (e.g., [39, 85]), or (2) create interactive flows where users can dynamically transition from rigid to deformable input (e.g., [189, 129]).

Deformable Input Replaces Rigid Input

Deformable input replaced rigid input particularly in mobile applications [47], where interfaces tend to maintain the same physical characteristics of their rigid counterparts [20, 3], and rigid input is technically still possible [152]. In most cases, rigid input was replaced using bend [3, 82], for navigating and zooming on maps [152, 45, 19, 20], but also as alternative input to touch-based pattern-lock authentication [108]. Burstyn et al. [20] showed that one-dimensional bend input is promising for interacting on flexible mobiles, as it highly correlates with Fitt's law [41], and may help improve control accuracy on mobiles. Beyond GUI-based interactions, Ernst et al. [35] showed how deformable input makes mobile technology accessible to visually impaired users. Overall, interfaces that replace rigid with deformable input tend towards new interactive paradigms, but are not yet untied from earlier ones.

Deformable Input Follows Shapes and Materials
Here, deformable input is used to explore new interactive paradigms that are untied from rigid interactions and interfaces. Even when used as input for WIMP applications, squeezable foam was used in place of mouse and keyboard for 3D sculpting in CAD applications [117]. Furthermore, mobile interaction is not the focus and the range of applications is wide (e.g., music [173, 191, 16, 157, 195, 113, 17], virtual 3D sculpting [155, 55, 181, 183], gaming [122], animation [12], data exploration [147, 204, 113]).

We noticed that deformable input here was used for two purposes: (1) *functional*, where deformations support functional aims, such as bending displays for privacy [125] or deform interfaces to match applications [43, 197, 170], and (2) *expressive*, where deformations enhance creative practices [173, 16, 109, 110, 193, 53, 25, 123], or promote new ways of manipulating and exploring digital contents [24, 62, 21, 204, 55, 28, 93, 162, 177, 154, 12, 184]. In both cases, individual gestures may be used, but become potentially endless as interactions are guided by shapes and materials. Hence, we found that deformable input can be *gesture-based*, but also *shape-based* or *material-based*.

Deformable input can follow shapes, when these become physical counterparts to the digital contents that they manipulate – much like Tangible User Interfaces (TUIs [63, 153, 176]). For instance, when used for virtual 3D sculpting [116], deformable interfaces allow users to physically deform the shape of digital mesh [117, 118, 159], or NURBS [9, 154]. In Flexpad [163], the dynamic deformation of flexible tablets is mapped to the movement of video-animations in real-time, while Clayodor [73] changes odor based how users shape the clay (e.g., a banana-like shape will smell accordingly).

However, unlike TUIs, deformable interfaces can be both generic and specific [173], depending on how I/O is mapped [125], and because their shapes can be dynamically modified to match contents and applications (e.g., [170, 43, 125, 197]). In that respect, they are also similar to shape-changing interfaces [135], but the way they change shape is based on user manipulation, rather than automated self-actuation.

Depending on material properties, deformable interfaces can be partially (e.g.,[197]), or radically deformed (e.g., [138]), to the point where the modified shapes have nothing in common with the initial ones [150, 188]. Examples are clay-based interfaces [138, 173, 188, 184, 150, 199, 31], where deformable

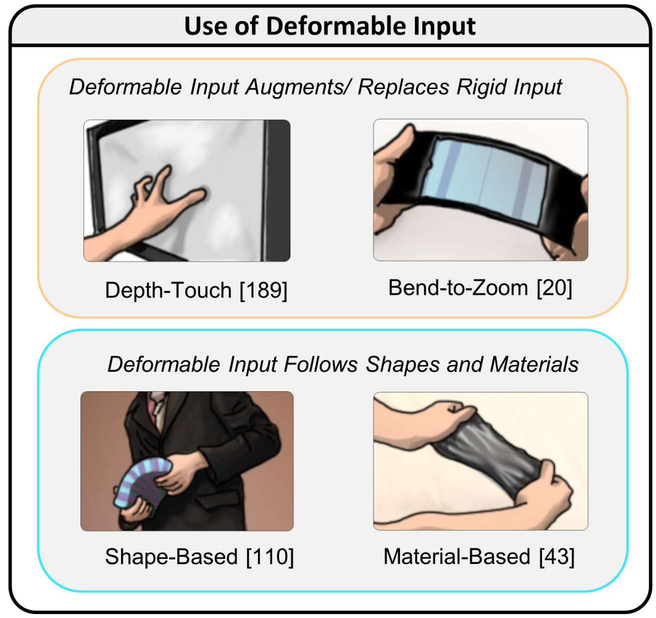

Figure 6: The way in which deformable input is used in relation to earlier HCI paradigms or to explore new ones; © Troiano & Boem

input follows the physical response and the dynamic affordances of the material, rather than specific gestures. As such, deformable interfaces like Illuminating Clay [62] and Digital Clay [138] promote interactions that are closer to sculpting compared, for instance, to bendable displays. With variable stiffness, deformable input follows dynamic materials that shift from soft to stiff and vice versa. In Claytric Surface [146], users can sculpt physical shapes on deformable displays when soft, and paint on the created shapes using touch input as the display goes stiff; here deformable interfaces express interesting potential for HCI, by bringing together qualities of tangible and shape-changing interfaces. However, further research is needed to fully exploit the potential of shape- and material-based deformable input.

DISCUSSION
We surveyed deformable interfaces, reviewed elements that form the basis of their design (i.e., shape, material), how they support deformable input, and how is deformable input used for interactive applications. We concentrated on input to integrate earlier reviews that focused more on output [135, 166, 142, 83, 133]. As such, we provided an extensive overview of design practices and solutions for non-rigid input, which were yet under-discussed. The review will be useful to designers and practitioners that wish to better understand non-rigid input and systematically approach its design. Furthermore, we identify under-explored research areas and propose research goals for future work with deformable interfaces and input.

Designing Deformable Interfaces and Input
We surveyed elements that form the basis of designing deformable interfaces and input. Regarding shape, if not designed after displays, their use is sparse and tied to designers' choices. Similarly, choices of deformable materials vary

greatly across interfaces and design practices are still experimental. We need studies that more systematically investigate how and which deformable input can be best supported by specific combinations of shapes and materials, and for which interactive applications. Integrating notions of psychophysics [46] and material perception [161, 11, 32] in future work may help advance knowledge in this area.

We showed how materials that shape-retain and vary stiffness allow deformable input to follow dynamic affordances. However, while dynamic affordances were investigated with shape change for output [174], they are yet unexplored with deformable interfaces; we would like to see similar studies that investigate dynamic affordances with deformable input. We see how deformable interfaces may enhance kinetic input, both gentle and aggressive [173], to express intentions [120], transmit energy in performative acts [16, 205, 109], or convey meaning through shape and movement [165, 120, 27, 177, 163]. Kinetic input with deformable interfaces represents a great opportunity for designing new HCI paradigms (e.g., punchable interfaces [91, 120], and should be further investigated.

We provided a thorough analysis of sensors and sensing techniques for deformable input and their implementation, which was briefly touched upon by previous review, and for displays only [166]. Furthermore, we analyzed and discussed mapping, which is key for understanding I/O relations with deformable interfaces, and how those relations determine (or are determined by) interaction design. Previous reviews did not discuss I/O mapping and we see great potential for future research in this area with deformable interfaces. For instance, deformable interfaces allow users to "touch" sounds. Further investigations of I/O relations with deformable interfaces may help make such analogies consistent between different sensory perceptions. We suggest that future work look at cross-modal correspondence [175, 160] and DMIs [23, 61, 40] to systematically investigate I/O relations with deformable interfaces.

Research Goals for Deformable Interfaces

There are research areas within deformable interfaces that remain under-explored. For instance, we have user-defined models of deformable interactions that wait to be implemented [178, 172], with yet little progress in that direction. Future work should further exploit such user-defined models and find suitable applications to those.

Deformable interfaces have shown promise for applications in expressive therapies, for instance through the use of deformable displays that act like music interfaces, and help autistic children in engaging in social interactions [105, 28]. However, the use of deformable interfaces for expressive therapy remains mostly unexplored. Deformable input has shown to support eyes-free interaction through haptic feedback provided by shapes and materials [190, 128, 173, 88, 53, 37, 98, 201, 124] which we encourage to further investigate.

We know that technology may allow sensing beyond two simultaneous deformations [144], but we still do not know: (1) what is the maximum number of deformations that users can control simultaneously? (2) how do users perceive individual deformations when they blur into one another? (3) what tasks are good fit to multidimensional deformable input and why? We suggest looking at studies of psychophysics to investigate perception of multidimensional deformable input [46], and integrality of input for finding fitting tasks [66].

Deformable input was often regarded as potentially more expressive compared to rigid input [102, 156, 26, 173]. However, since control expressiveness may be relative to tasks and how refined the I/O mapping is, one may argue that rigid interfaces can be used expressively too [111]. At present, we do not know how (and if) the above claims are true (i.e., deformable more expressive than rigid), but we do encourage more comparative studies (e.g., [104]) that investigate rigid vs deformable input.

We are witnessing the emergence of bendable and foldable displays in the industry [76, 141, 130, 56, 2, 148, 186], but reducing deformable interfaces to "flexible displays" only may be risky. For instance, our review shows that deformable interfaces are more than just "bendable", and they move HCI paradigms to yet under-explored territories when deformable input follows shapes and materials (e.g.,[109, 16, 173]). However, while research on displays and GUI is well-grounded in HCI, interfaces that are not display remain in the realm of highly experimental work, and answering the question "what is a deformable interface interface really useful for?" remains hard [173]. For instance, what is the "killer app" for deformable interfaces and who could benefit from using existing interfaces (e.g., Illuminating Clay [131])? To answer those questions, we need to ground existing prototypes (e.g., deformable interfaces for 3D sculpting [117] and music [16]) in real-life, and let professionals use them and give feedback.

As such, we encourage studies based on participatory design (PD) [15], which directly involve users and stakeholders by grounding the design of deformable interfaces in their needs, as well as *in-the-wild* studies [54], to obtain spontaneous reactions from users that are unlikely in lab-controlled studies. Furthermore, we need longitudinal studies [173], that observe how users learn to master deformable input over time. Finally, we encourage future reviews to include deformable interfaces from other interdisciplinary fields and potentially relevant sources, such as interactive arts and design.

CONCLUSION

We reviewed deformable interfaces and input based on 131 papers. We outlined their main design characteristics, discussed use of deformable input, and identified under-explored research areas. We hope that our work will contribute a productive discussions among designers and researchers that wish to further investigate deformable interfaces and non-rigid HCI.

ACKNOWLEDGMENTS

We would like to thank Kasper Hornbaek, Monica Tentori, Hiroo Iwata, Casper Harteveld, and Alessio Chierico for their precious feedback on the draft. We would also like to thank Rannvá Glerfoss and Igor *Kaneda* Knowles for their kind support.

REFERENCES

[1] 2013. Kinect Hacks | Kreek Prototype 2.1. (2013). http://www.kinecthacks.com/kreek-prototype-2-1/ Retrieved: 2018-07-20.

[2] 2018. Apple continues their work on a Folding iPhone by focusing on new Flexible Sensors, a new Flexible Battery & Circuits. Patently Apple. (13 Sep 2018).

[3] Teemu T. Ahmaniemi, Johan Kildal, and Merja Haveri. 2014. What is a Device Bend Gesture Really Good for?. In *Proceedings of the 32Nd Annual ACM Conference on Human Factors in Computing Systems (CHI '14)*. ACM, New York, NY, USA, 3503–3512. DOI: http://dx.doi.org/10.1145/2556288.2557306

[4] Jason Alexander, Anne Roudaut, Jürgen Steimle, Kasper Hornbæk, Miguel Bruns Alonso, Sean Follmer, and Timothy Merritt. 2018. Grand Challenges in Shape-Changing Interface Research. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. ACM, New York, NY, USA, Article 299, 14 pages. DOI: http://dx.doi.org/10.1145/3173574.3173873

[5] Rufino Ansara and Audrey Girouard. 2014. Augmenting Bend Gestures with Pressure Zones on Flexible Displays. In *Proceedings of the 16th International Conference on Human-computer Interaction with Mobile Devices; Services (MobileHCI '14)*. ACM, New York, NY, USA, 531–536. DOI: http://dx.doi.org/10.1145/2628363.2634228

[6] Felipe Bacim, Mike Sinclair, and Hrvoje Benko. 2012. Challenges of Multitouch Interaction on Deformable Surfaces. In *In ITS'12. Beyond Flat Displays Workshop*. ACM, Cambridge, Massachusetts, USA. http://displayworkshop.media.mit.edu/ITS2012/downloads/paper-Bacim.pdf

[7] Felipe Bacim, Mike Sinclair, and Hrvoje Benko. 2013. Understanding Touch Selection Accuracy on Flat and Hemispherical Deformable Surfaces. In *Proceedings of Graphics Interface 2013 (GI '13)*. Canadian Information Processing Society, Canada, 197–204. http://dl.acm.org/citation.cfm?id=2532129.2532163

[8] Gavin Bailey, Deepak Sahoo, and Matt Jones. 2017. Paper for E-Paper: Towards Paper Like Tangible Experience Using E-Paper. In *Proceedings of the 2017 ACM International Conference on Interactive Surfaces and Spaces (ISS '17)*. ACM, New York, NY, USA, 446–449. DOI: http://dx.doi.org/10.1145/3132272.3132298

[9] Ravin Balakrishnan, George Fitzmaurice, Gordon Kurtenbach, and Karan Singh. 1999. Exploring Interactive Curve and Surface Manipulation Using a Bend and Twist Sensitive Input Strip. In *Proceedings of the 1999 Symposium on Interactive 3D Graphics (I3D '99)*. ACM, New York, NY, USA, 111–118. DOI: http://dx.doi.org/10.1145/300523.300536

[10] Wouter M. Bergmann Tiest. 2010. Tactual perception of material properties. *Vision Research* 50, 24 (2010), 2775 – 2782. DOI: http://dx.doi.org/0.1016/j.visres.2010.10.005

[11] Wouter M. Bergmann Tiest and Astrid M. L. Kappers. 2009. Cues for Haptic Perception of Compliance. *IEEE Transactions on Haptics* 2, 4 (Oct 2009), 189–199. DOI: http://dx.doi.org/10.1109/TOH.2009.16

[12] Tristan Beven, Thuong Hoang, Marcus Carter, and Bernd Ploderer. 2016. HandLog: A Deformable Tangible Device for Continuous Input Through Finger Flexion. In *Proceedings of the 28th Australian Conference on Computer-Human Interaction (OzCHI '16)*. ACM, New York, NY, USA, 595–604. DOI: http://dx.doi.org/10.1145/3010915.3010933

[13] H. R. Beyer and K. Holtzblatt. 1997. *Contextual Design: Defining Customer-Centered Systems*. Morgan Kaufmann, 1st Edition, Burlington, MA, USA.

[14] José María Blanco, Pascal Landry, Sebastián Mealla C., Emanuela Mazzone, and Narcís Parés. 2010. PIPLEX: Tangible Experience in an Augmented Reality Video Game. In *Proceedings of the 9th International Conference on Interaction Design and Children (IDC '10)*. ACM, New York, NY, USA, 274–277. DOI: http://dx.doi.org/10.1145/1810543.1810590

[15] Kerl Bodker, Finn Kensing, and Jesper Simonsen. 2014. *Participatory It Design: Designing for Business and Workplace Realities*. MIT Press.

[16] Alberto Boem. 2014. SculpTon: A malleable tangible interface for sound sculpting. In *Proceedings of the 2014 Joint International Computer Music Conference and Sound and Music Computing (ICMC+SMC)*. ICMA, San Francisco, CA, USA, 737–743. https://quod.lib.umich.edu/i/icmc/bbp2372.2014.115/1

[17] Bert Bongers and Yolande Harris. 2002. A Structured Instrument Design Approach: The Video-Organ. In *Proceedings of the International Conference on New Interfaces for Musical Expression* (24-26 May, 2002). Dublin, Ireland, 18–23. http://www.nime.org/proceedings/2002/nime2002_018.pdf

[18] Anders Brodersen, Monika Büscher, Michael Christensen, Mette Agger Eriksen, Kaj Grønbæk, Jannie Friis Kristensen, Gunnar Kramp, Peter Krogh, Martin Ludvigsen, Preben Holst Mogensen, Michael Bang Nielsen, Dan Shapiro, and Peter Orbaek. 2007. The Disappearing Computer. Springer-Verlag, Berlin, Heidelberg, Chapter Spatial Computing and Spatial Practices, 77–95. http://dl.acm.org/citation.cfm?id=1768246.1768251

[19] Jesse Burstyn, Amartya Banerjee, and Roel Vertegaal. 2013. FlexView: An Evaluation of Depth Navigation on Deformable Mobile Devices. In *Proceedings of the 7th International Conference on Tangible, Embedded and Embodied Interaction (TEI '13)*. ACM, New York, NY, USA, 193–200. DOI: http://dx.doi.org/10.1145/2460625.2460655

[20] Jesse Burstyn, Juan Pablo Carrascal, and Roel Vertegaal. 2016. Fitts' Law and the Effects of Input Mapping and Stiffness on Flexible Display Interactions. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. ACM, New York, NY, USA, 3649–3658. DOI: http://dx.doi.org/10.1145/2858036.2858383

[21] Simon Butscher, Maximilian Dürr, and Harald Reiterer. 2017. InformationSense: Trade-offs for the Design and the Implementation of a Large Highly Deformable Cloth Display. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 1, 2, Article 7 (jun 2017), 28 pages. DOI: http://dx.doi.org/10.1145/3090053

[22] William D. Callister. 2004. *Fundamentals of Materials Science and Engineering*. John Wiley and Sons, USA.

[23] Baptiste Caramiaux, Jules Françoise, Norbert Schnell, and Frédéric Bevilacqua. 2014. Mapping Through Listening. *Computer Music Journal* 38, 3 (2014), 34–48. DOI:http://dx.doi.org/10.1162/COMJ_a_00255

[24] Alvaro Cassinelli and Masatoshi Ishikawa. 2005. Khronos Projector. In *ACM SIGGRAPH 2005 Emerging Technologies (SIGGRAPH '05)*. ACM, New York, NY, USA, Article 10. DOI: http://dx.doi.org/10.1145/1187297.1187308

[25] Angela Chang and Hiroshi Ishii. 2007. 2007. Zstretch: A Stretchy Fabric Music Controller. In *In Proc. NIME'07. 7th International Conference on New Interfaces for Musical Expression*. ACM, New York, NY, USA, 46–49. DOI:http://dx.doi.org/10.1145/1279740.1279746

[26] Victor Cheung, Alexander Keith Eady, and Audrey Girouard. 2018. Deformable Controllers: Fabrication and Design to Promote Novel Hand Gestural Interaction Mechanisms. In *Proceedings of the Twelfth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '18)*. ACM, New York, NY, USA, 732–735. DOI: http://dx.doi.org/10.1145/3173225.3173332

[27] Chin-yu Chien, Cheng-Yuan Li, Liwei Chan, Yi-Chi Liao, Rong-Hao Liang, Hao-hua Chu, and Bing-Yu Chen. 2015. fStrip: A Malleable Shape-retaining Wearable Strip for Interface On-demand. In *Adjunct Proceedings of the 2015 ACM International Joint Conference on Pervasive and Ubiquitous Computing and Proceedings of the 2015 ACM International Symposium on Wearable Computers (UbiComp/ISWC'15 Adjunct)*. ACM, New York, NY, USA, 105–108. DOI: http://dx.doi.org/10.1145/2800835.2800883

[28] Franceli L. Cibrian, Oscar Peña, Deysi Ortega, and Monica Tentori. 2017. BendableSound: An elastic multisensory surface using touch-based interactions to assist children with severe autism during music therapy. *International Journal of Human-Computer Studies* 107 (2017), 22 – 37. DOI: http://dx.doi.org/10.1016/j.ijhcs.2017.05.003

[29] Marcelo Coelho and Jamie Zigelbaum. 2011. Shape-changing Interfaces. *Personal Ubiquitous Comput.* 15, 2 (feb 2011), 161–173. DOI: http://dx.doi.org/10.1007/s00779-010-0311-y

[30] Farshad Daliri and Audrey Girouard. 2016. Visual Feedforward Guides for Performing Bend Gestures on Deformable Prototypes. In *Proceedings of the 42Nd Graphics Interface Conference (GI '16)*. Canadian Human-Computer Communications Society, School of Computer Science, University of Waterloo, Waterloo, Ontario, Canada, 209–216. DOI: http://dx.doi.org/10.20380/GI2016.27

[31] Brendan Dawes. 2006. *Analog In, Digital Out: Brendan Dawes on Interaction Design*. New Riders Publishing, USA.

[32] Massimiliano Di Luca. 2014. *Multisensory Softness: Perceived Compliance from Multiple Sources of Information*. Springer. DOI: http://dx.doi.org/10.1007/978-1-4471-6533-0h

[33] Connor Dickie, Nicholas Fellion, and Roel Vertegaal. 2012. FlexCam: Using Thin-film Flexible OLED Color Prints As a Camera Array. In *CHI '12 Extended Abstracts on Human Factors in Computing Systems (CHI EA '12)*. ACM, New York, NY, USA, 1051–1054. DOI:http://dx.doi.org/10.1145/2212776.2212383

[34] Rhys Duindam, Diemo Schwarz, and Hans Leeuw. 2015. Tingle: A Digital Music Controller Re-Capturing the Acoustic Instrument Experience. In *Proceedings of the International Conference on New Interfaces for Musical Expression*, Edgar Berdahl and Jesse Allison (Eds.). Louisiana State University, Baton Rouge, Louisiana, USA, 219–222. http://www.nime.org/proceedings/2015/nime2015_319.pdf

[35] Matthew Ernst and Audrey Girouard. 2016a. Bending Blindly: Exploring Bend Gestures for the Blind. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems (CHI EA '16)*. ACM, New York, NY, USA, 2088–2096. DOI:http://dx.doi.org/10.1145/2851581.2892303

[36] Matthew Ernst and Audrey Girouard. 2016b. Exploring Haptics for Learning Bend Gestures for the Blind. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems (CHI EA '16)*. ACM, New York, NY, USA, 2097–2104. DOI:http://dx.doi.org/10.1145/2851581.2892382

[37] Matthew Ernst, Travis Swan, Victor Cheung, and Audrey Girouard. 2017. Typhlex: Exploring Deformable Input for Blind Users Controlling a Mobile Screen Reader. *IEEE Pervasive Computing* 16, 4 (October 2017), 28–35. DOI: http://dx.doi.org/10.1109/MPRV.2017.3971123

[38] Elias Fares, Victor Cheung, and Audrey Girouard. 2017. Effects of Bend Gesture Training on Learnability and Memorability in a Mobile Game. In *Proceedings of the 2017 ACM International Conference on Interactive Surfaces and Spaces (ISS '17)*. ACM, New York, NY, USA, 240–245. DOI: http://dx.doi.org/10.1145/3132272.3134142

[39] Nicholas Fellion, Thomas Pietrzak, and Audrey Girouard. 2017. FlexStylus: Leveraging Bend Input for Pen Interaction. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology (UIST '17)*. ACM, New York, NY, USA, 375–385. DOI: http://dx.doi.org/10.1145/3126594.3126597

[40] Sidney Fels, Ashley Gadd, and Axel Mulder. 2002. Mapping Transparency Through Metaphor: Towards More Expressive Musical Instruments. *Organized Sound* 7, 2 (Aug. 2002), 109–126. DOI: http://dx.doi.org/10.1017/S1355771802002042

[41] Paul M. Fitts. 1954. The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology* 47, 6 (1954), 381–391. DOI: http://dx.doi.org/10.1037/h0055392

[42] Sean Follmer, Micah Johnson, Edward Adelson, and Hiroshi Ishii. 2011. deForm: An Interactive Malleable Surface for Capturing 2.5D Arbitrary Objects, Tools and Touch. In *Proceedings of the 24th Annual ACM Symposium on User Interface Software and Technology (UIST '11)*. ACM, New York, NY, USA, 527–536. DOI: http://dx.doi.org/10.1145/2047196.2047265

[43] Sean Follmer, Daniel Leithinger, Alex Olwal, Nadia Cheng, and Hiroshi Ishii. 2012. Jamming User Interfaces: Programmable Particle Stiffness and Sensing for Malleable and Shape-changing Devices. In *Proceedings of the 25th Annual ACM Symposium on User Interface Software and Technology (UIST '12)*. ACM, New York, NY, USA, 519–528. DOI: http://dx.doi.org/10.1145/2380116.2380181

[44] Sean Follmer, Daniel Leithinger, Alex Olwal, Akimitsu Hogge, and Hiroshi Ishii. 2013. inFORM: Dynamic Physical Affordances and Constraints Through Shape and Object Actuation. In *Proceedings of the 26th Annual ACM Symposium on User Interface Software and Technology (UIST '13)*. ACM, New York, NY, USA, 417–426. DOI: http://dx.doi.org/10.1145/2501988.2502032

[45] David T. Gallant, Andrew G. Seniuk, and Roel Vertegaal. 2008. Towards More Paper-like Input: Flexible Input Devices for Foldable Interaction Styles. In *Proceedings of the 21st Annual ACM Symposium on User Interface Software and Technology (UIST '08)*. ACM, New York, NY, USA, 283–286. DOI: http://dx.doi.org/10.1145/1449715.1449762

[46] George A. Gescheider. 2013. *Psychophysics : The Fundamentals*. Psychology Press, USA. DOI: http://dx.doi.org/10.4324/9780203774458

[47] Audrey Girouard, Jessica Lo, Md Riyadh, Farshad Daliri, Alexander Keith Eady, and Jerome Pasquero. 2015. One-Handed Bend Interactions with Deformable Smartphones. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*. ACM, New York, NY, USA, 1509–1518. DOI:http://dx.doi.org/10.1145/2702123.2702513

[48] Barney Glaser and Anselm Strauss. 2000. *The Discovery of Grounded Theory: Strategies for Qualitative Research*. Routledge, USA.

[49] Oliver Glauser, Daniele Panozzo, Otmar Hilliges, and Olga Sorkine-Hornung. 2018. Deformation Capture via Self-Sensing Capacitive Arrays. *CoRR* abs/1804.04013 (2018). http://arxiv.org/abs/1804.04013

[50] Antonio Gomes, Lahiru Priyadarshana, Juan Pablo Carrascal, and Roel Vertegaal. 2016. WhammyPhone: Exploring Tangible Audio Manipulation Using Bend Input on a Flexible Smartphone. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology (UIST '16 Adjunct)*. ACM, New York, NY, USA, 159–161. DOI: http://dx.doi.org/10.1145/2984751.2985742

[51] Daniel Gotsch, Xujing Zhang, Juan Pablo Carrascal, and Roel Vertegaal. 2016. HoloFlex: A Flexible Light-Field Smartphone with a Microlens Array and a P-OLED Touchscreen. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology (UIST '16)*. ACM, New York, NY, USA, 69–79. DOI: http://dx.doi.org/10.1145/2984511.2984524

[52] Saul Greenberg, Sebastian Boring, Jo Vermeulen, and Jakub Dostal. 2014. Dark Patterns in Proxemic Interactions: A Critical Perspective. In *Proceedings of the 2014 Conference on Designing Interactive Systems (DIS '14)*. ACM, New York, NY, USA, 523–532. DOI: http://dx.doi.org/10.1145/2598510.2598541

[53] Mick Grierson and Chris Kiefer. 2013. NoiseBear: A Malleable Wireless Controller Designed In Participation with Disabled Children. In *Proceedings of the International Conference on New Interfaces for Musical Expression*. Daejeon, Republic of Korea, 413–416. http://nime.org/proceedings/2013/nime2013_227.pdf

[54] Erik Grönvall, Sofie Kinch, Marianne Graves Petersen, and Majken K. Rasmussen. 2014. Causing Commotion with a Shape-changing Bench: Experiencing Shape-changing Interfaces in Use. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '14)*. ACM, New York, NY, USA, 2559–2568. DOI: http://dx.doi.org/10.1145/2556288.2557360

[55] Jaehyun Han, Jiseong Gu, and Geehyuk Lee. 2014. Trampoline: A Double-sided Elastic Touch Device for Creating Reliefs. In *Proceedings of the 27th Annual ACM Symposium on User Interface Software and Technology (UIST '14)*. ACM, New York, NY, USA, 383–388. DOI: http://dx.doi.org/10.1145/2642918.2647381

[56] Ed Hardy. 2018. Apple lays groundwork for bendable iPhone. Cult of Mac. (April 2018).

[57] John Hardy, Christian Weichel, Faisal Taher, John Vidler, and Jason Alexander. 2015. ShapeClip: Towards Rapid Prototyping with Shape-Changing Displays for Designers. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*. ACM, New York, NY, USA, 19–28. DOI: http://dx.doi.org/10.1145/2702123.2702599

[58] Shuji Hashimoto and Hideyuki Sawada. 2005. A Grasping Device to Sense Hand Gesture for Expressive Sound Generation. *Journal of New Music Research* 34, 1 (2005), 115–123. DOI: http://dx.doi.org/10.1080/09298210500124232

[59] Gero Herkenrath, Thorsten Karrer, and Jan Borchers. 2008. Twend: Twisting and Bending As New Interaction Gesture in Mobile Devices. In *CHI '08 Extended Abstracts on Human Factors in Computing Systems (CHI EA '08)*. ACM, New York, NY, USA, 3819–3824. DOI:http://dx.doi.org/10.1145/1358628.1358936

[60] David Holman, Audrey Girouard, Hrvoje Benko, and Roel Vertegaal. 2013. The Design of Organic User Interfaces: Shape, Sketching and Hypercontext. *Interacting with Computers* 25, 2 (feb 2013), 133–142. DOI:http://dx.doi.org/10.1093/iwc/iws018

[61] Andy Hunt, Marcelo M. Wanderley, and Ross Kirk. 2000. Towards a model for instrumental mapping in expert musical interaction. In *Proceedings of the 2000 International Computer Music Conference*. Berlin, Germany.

[62] H. Ishii, C. Ratti, B. Piper, Y. Wang, A. Biderman, and E. Ben-Joseph. 2004. Bringing Clay and Sand into Digital Design — Continuous Tangible user Interfaces. *BT Technology Journal* 22, 4 (oct 2004), 287–299. DOI: http://dx.doi.org/10.1023/B:BTTJ.0000047607.16164.16

[63] Hiroshi Ishii and Brygg Ullmer. 1997. Tangible Bits: Towards Seamless Interfaces Between People, Bits and Atoms. In *Proceedings of the ACM SIGCHI Conference on Human Factors in Computing Systems (CHI '97)*. ACM, New York, NY, USA, 234–241. DOI: http://dx.doi.org/10.1145/258549.258715

[64] Hiroo Iwata, Hiroaki Yano, Fumitaka Nakaizumi, and Ryo Kawamura. 2001. Project FEELEX: Adding Haptic Surface to Graphics. In *Proceedings of the 28th Annual Conference on Computer Graphics and Interactive Techniques (SIGGRAPH '01)*. ACM, New York, NY, USA, 469–476. DOI: http://dx.doi.org/10.1145/383259.383314

[65] Hiroo Iwata, Hiroaki Yano, and Naoto Ono. 2005. Volflex. In *ACM SIGGRAPH 2005 Emerging Technologies (SIGGRAPH '05)*. ACM, New York, NY, USA, Article 31. DOI: http://dx.doi.org/10.1145/1187297.1187329

[66] Robert J. K. Jacob, Linda E. Sibert, Daniel C. McFarlane, and M. Preston Mullen, Jr. 1994. Integrality and Separability of Input Devices. *ACM Trans. Comput.-Hum. Interact.* 1, 1 (mar 1994), 3–26. DOI: http://dx.doi.org/10.1145/174630.174631

[67] Dhruv Jain, Graysen Babbitt, Emma Pearl Canning, and Willmer-Shiles. 2016. Towards Interactive Force-Sensitive Digitally Encoded Materials for Architectural Models and Construction. In *Workshop paper on Future of Human-Building Interaction of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. http://human-ist.unifr.ch/sites/human-ist.unifr.ch/files/7-CHI2016-NervousBlocks_v5.0_DJ_CAMERA.pdf

[68] Yvonne Jansen. 2010. Mudpad: Fluid Haptics for Multitouch Surfaces. In *CHI '10 Extended Abstracts on Human Factors in Computing Systems (CHI EA '10)*. ACM, New York, NY, USA, 4351–4356. DOI: http://dx.doi.org/10.1145/1753846.1754152

[69] Alexander Refsum Jensenius and Michael J. Lyons. 2017. *A NIME Reader*. Springer, Cham. DOI: http://dx.doi.org/10.1007/978-3-319-47214-0

[70] Alexander Refsum Jensenius and Arve Voldsund. 2012. The Music Ball Project: Concept, Design, Development, Performance. In *Proceedings of the International Conference on New Interfaces for Musical Expression*. University of Michigan, Ann Arbor, Michigan. http://www.nime.org/proceedings/2012/nime2012_161.pdf

[71] Martin Kaltenbrunner. 2009. reacTIVision and TUIO: A Tangible Tabletop Toolkit. In *Proceedings of the ACM International Conference on Interactive Tabletops and Surfaces (ITS '09)*. ACM, New York, NY, USA, 9–16. DOI:http://dx.doi.org/10.1145/1731903.1731906

[72] Kazuto Kamiyama, Hiroyuki Kajimoto, Naoki Kawakami, and Susumu Tachi. 2004. Evaluation of a vision-based tactile sensor. In *IEEE International Conference on Robotics and Automation, 2004. Proceedings. ICRA '04. 2004*, Vol. 2. 1542–1547 Vol.2. DOI:http://dx.doi.org/10.1109/ROBOT.2004.1308043

[73] C. H.-L. Kao, E. Dreshaj, J. Amores, S.-w. Leigh, X. Benavides, P. Maes, K. Perlin, and H. Ishii. 2015. Clayodor: Retrieving Scents Through the Manipulation of Malleable Material. In *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '15)*. ACM, New York, NY, USA, 697–702. DOI: http://dx.doi.org/10.1145/2677199.2688814

[74] Maria Karam and M. C. Schraefel. 2005. *A taxonomy of gestures in human computer interactions*. Technical Report. University of Southampton.

[75] Yuichiro Katsumoto, Satoru Tokuhisa, and Masa Inakage. 2013. Ninja Track: Design of Electronic Toy Variable in Shape and Flexibility. In *Proceedings of the 7th International Conference on Tangible, Embedded and Embodied Interaction (TEI '13)*. ACM, New York, NY, USA, 17–24. DOI: http://dx.doi.org/10.1145/2460625.2460628

[76] Sean Keach. 2018. INTO THE FOLD LG foldable smartphone leaks as a possible Samsung Galaxy X rival – we reveal secret pictures of the mystery phone. The Sun. (22 Jan 2018).

[77] Chris Kiefer. 2010. A Malleable Interface for Sonic Exploration. In *Proceedings of the International Conference on New Interfaces for Musical Expression*. Sydney, Australia, 291–296. http://www.nime.org/proceedings/2010/nime2010_291.pdf

[78] Johan Kildal. 2012. Interacting with Deformable User Interfaces: Effect of Material Stiffness and Type of Deformation Gesture. In *Proceedings of the 7th International Conference on Haptic and Audio Interaction Design (HAID'12)*. Springer-Verlag, Berlin, 71–80. DOI: http://dx.doi.org/10.1007/978-3-642-32796-4_8

[79] Johan Kildal and Marion Boberg. 2013. Feel the Action: Dynamic Tactile Cues in the Interaction with Deformable Uis. In *In CHI'13 Extended Abstracts on Human Factors in Computing Systems*. ACM, New York, NY, USA, 1563–1568. DOI: http://dx.doi.org/10.1145/2468356.2468636

[80] Johan Kildal, Andrés Lucero, and Marion Boberg. 2013. Twisting Touch: Combining Deformation and Touch As Input Within the Same Interaction Cycle on Handheld Devices. In *Proceedings of the 15th International Conference on Human-computer Interaction with Mobile Devices and Services (MobileHCI '13)*. ACM, New York, NY, USA, 237–246. DOI: http://dx.doi.org/10.1145/2493190.2493238

[81] Johan Kildal, Susanna Paasovaara, and Viljakaisa Aaltonen. 2012. Kinetic Device: Designing Interactions with a Deformable Mobile Interface. In *CHI '12 Extended Abstracts on Human Factors in Computing Systems (CHI EA '12)*. ACM, New York, NY, USA, 1871–1876. DOI: http://dx.doi.org/10.1145/2212776.2223721

[82] Johan Kildal and Graham Wilson. 2012. Feeling It: The Roles of Stiffness, Deformation Range and Feedback in the Control of Deformable Ui. In *Proceedings of the 14th ACM International Conference on Multimodal Interaction (ICMI '12)*. ACM, New York, NY, USA, 393–400. DOI: http://dx.doi.org/10.1145/2388676.2388766

[83] Hyunyoung Kim, Celine Coutrix, and Anne Roudaut. 2018. Morphees+: Studying Everyday Reconfigurable Objects for the Design and Taxonomy of Reconfigurable UIs. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. ACM, New York, NY, USA, Article 619, 14 pages. DOI: http://dx.doi.org/10.1145/3173574.3174193

[84] Jaemin Kim, Jongsu Lee, Donghee Son, Moon Kee Choi, and Dae-Hyeong Kim. 2016. Deformable devices with integrated functional nanomaterials for wearable electronics. *Nano Convergence* 3, 1 (15 Mar 2016), 4. DOI:http://dx.doi.org/10.1186/s40580-016-0062-1

[85] Seoktae Kim, Hyunjung Kim, Boram Lee, Tek-Jin Nam, and Woohun Lee. 2008. Inflatable Mouse: Volume-adjustable Mouse with Air-pressure-sensitive Input and Haptic Feedback. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '08)*. ACM, New York, NY, USA, 211–224. DOI: http://dx.doi.org/10.1145/1357054.1357090

[86] Phil Kingsley. 2013. eTable: A haptic elastic table for 3D multi-touch interations. (2013). Retrieved September 15, 2019 from https://www.youtube.com/watch?v=GY22EU9Z-0g.

[87] Yuichiro Kinoshita, Masato Nishio, Shota Shiraga, and Kentaro Go. 2018. Investigation of Pleasantness in the Manipulation of Deformable Interfaces for Musical Expression. In *Linkoping Electronic Conference Proceedings*. Linkoping University Electronic Press, Linköpings universitet, 315–324.

[88] Konstantin Klamka and Raimund Dachselt. 2015. Elasticcon: Elastic Controllers for Casual Interaction. In *Proceedings of the 17th International Conference on Human-Computer Interaction with Mobile Devices and Services (MobileHCI '15)*. ACM, New York, NY, USA, 410–419. DOI: http://dx.doi.org/10.1145/2785830.2785849

[89] Roberta L. Klatzky, Dianne Pawluk, and Angelika Peer. 2013. Haptic Perception of Material Properties and Implications for Applications. *Proc. IEEE* 101, 9 (Sept 2013), 2081–2092. DOI: http://dx.doi.org/10.1109/JPROC.2013.2248691

[90] Jeffrey Tzu Kwan Valino Koh, Kasun Karunanayaka, Jose Sepulveda, Mili J. Tharakan, Manoj Krishnan, and Adrian D. Cheok. 2011. Liquid Interface: A Malleable, Transient, Direct-touch Interface. *Comput. Entertain.* 9, 2, Article 7 (jul 2011), 8 pages. DOI: http://dx.doi.org/10.1145/1998376.1998378

[91] Hyosun Kwon, Seok-Hyung Bae, Hwan Kim, and Woohun Lee. 2012. Inflated Roly-poly. In *Proceedings of the Sixth International Conference on Tangible, Embedded and Embodied Interaction (TEI '12)*. ACM, New York, NY, USA, 189–192. DOI: http://dx.doi.org/10.1145/2148131.2148172

[92] Byron Lahey, Audrey Girouard, Winslow Burleson, and Roel Vertegaal. 2011. PaperPhone: Understanding the Use of Bend Gestures in Mobile Devices with Flexible Electronic Paper Displays. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '11)*. ACM, New York, NY, USA, 1303–1312. DOI: http://dx.doi.org/10.1145/1978942.1979136

[93] Chris Larson, Josef Spjut, Ross A. Knepper, and Robert F. Shepherd. 2017. OrbTouch: Recognizing Human Touch in Deformable Interfaces with Deep Neural Networks. *CoRR* abs/1706.02542 (2017). http://arxiv.org/abs/1706.02542

[94] Vincent LeClerc, Amanda Parkes, and Hiroshi Ishii. 2007. Senspectra: A Computationally Augmented Physical Modeling Toolkit for Sensing and Visualization of Structural Strain. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '07)*. ACM, New York, NY, USA, 801–804. DOI: http://dx.doi.org/10.1145/1240624.1240744

[95] Susan J. Lederman and Roberta L. Klatzky. 2009. Haptic perception: A tutorial. *Attention, Perception, & Psychophysics* 71, 7 (01 Oct 2009), 1439–1459. DOI: http://dx.doi.org/10.3758/APP.71.7.1439

[96] Sang-Su Lee, Sohyun Kim, Bopil Jin, Eunji Choi, Boa Kim, Xu Jia, Daeeop Kim, and Kun-pyo Lee. 2010. How Users Manipulate Deformable Displays As Input Devices. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '10)*. ACM, New York, NY, USA, 1647–1656. DOI: http://dx.doi.org/10.1145/1753326.1753572

[97] Sang-su Lee, Youn-kyung Lim, and Kun-Pyo Lee. 2012. Exploring the Effects of Size on Deformable User Interfaces. In *Proceedings of the 14th International Conference on Human-computer Interaction with Mobile Devices and Services Companion (MobileHCI '12)*. ACM, New York, NY, USA, 89–94. DOI: http://dx.doi.org/10.1145/2371664.2371682

[98] Sang-Su Lee, Seungwoo Maeng, Daeeop Kim, Kun-Pyo Lee, Wonkyum Lee, Sangsik Kim, and Sungkwan Jung. 2011. FlexRemote: Exploring the Effectiveness of Deformable User Interface as an Input Device for TV. In *HCI International 2011 – Posters' Extended Abstracts*, Constantine Stephanidis (Ed.). Springer, Berlin, 62–65. DOI:http://dx.doi.org/10.1007/978-3-642-22095-1_13

[99] Daniel Leithinger, Sean Follmer, Alex Olwal, Samuel Luescher, Akimitsu Hogge, Jinha Lee, and Hiroshi Ishii. 2013. Sublimate: State-changing Virtual and Physical Rendering to Augment Interaction with Shape Displays. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '13)*. ACM, New York, NY, USA, 1441–1450. DOI: http://dx.doi.org/10.1145/2470654.2466191

[100] Daniel Leithinger and Hiroshi Ishii. 2010. Relief: A Scalable Actuated Shape Display. In *Proceedings of the Fourth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '10)*. ACM, New York, NY, USA, 221–222. DOI: http://dx.doi.org/10.1145/1709886.1709928

[101] Julian Lepinski and Roel Vertegaal. 2011. Cloth Displays: Interacting with Drapable Textile Screens. In *Proceedings of the Fifth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '11)*. ACM, New York, NY, USA, 285–288. DOI: http://dx.doi.org/10.1145/1935701.1935765

[102] Jessica Lo and Audrey Girouard. 2017. Bendy: Exploring Mobile Gaming with Flexible Devices. In *Proceedings of the Eleventh International Conference on Tangible, Embedded, and Embodied Interaction (TEI '17)*. ACM, New York, NY, USA, 163–172. DOI: http://dx.doi.org/10.1145/3024969.3024970

[103] Qiuyu Lu, Chengpeng Mao, Liyuan Wang, and Haipeng Mi. 2016. LIME: LIquid MEtal Interfaces for Non-Rigid Interaction. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology (UIST '16)*. ACM, New York, NY, USA, 449–452. DOI: http://dx.doi.org/10.1145/2984511.2984562

[104] Aurélien Lucchi, Patrick Jermann, Guillaume Zufferey, and Pierre Dillenbourg. 2010. An Empirical Evaluation of Touch and Tangible Interfaces for Tabletop Displays. In *Proceedings of the Fourth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '10)*. ACM, New York, NY, USA, 177–184. DOI: http://dx.doi.org/10.1145/1709886.1709917

[105] Cathy A. Malchiodi. 2006. *Expressive therapies*. Guilford Press, USA.

[106] Joseph Malloch, Stephen Sinclair, Avrum Hollinger, and Marcelo M. Wanderley. 2011. *Input Devices and Music Interaction*. Springer Berlin Heidelberg, Berlin, Heidelberg, 67–83. DOI: http://dx.doi.org/10.1007/978-3-642-22291-7_5

[107] J. Malloch, S. Sinclair, and M. M. Wanderley. 2018. Generalized Multi-Instance Control Mapping for Interactive Media Systems. *IEEE MultiMedia* 25, 1 (Jan 2018), 39–50. DOI: http://dx.doi.org/10.1109/MMUL.2018.112140028

[108] Sana Maqsood, Sonia Chiasson, and Audrey Girouard. 2016. Bend Passwords: Using Gestures to Authenticate on Flexible Devices. *Personal Ubiquitous Comput.* 20, 4 (aug 2016), 573–600. DOI: http://dx.doi.org/10.1007/s00779-016-0928-6

[109] Martin Marier. 2010. The Sponge A Flexible Interface. In *Proceedings of the International Conference on New Interfaces for Musical Expression*. Sydney, Australia, 356–359. http://www.nime.org/proceedings/2010/nime2010_356.pdf

[110] Martin Marier. 2014. Designing Mappings for the Sponge: Towards Spongistic Music. In *Proceedings of the International Conference on New Interfaces for Musical Expression*. Goldsmiths, University of London, London, United Kingdom, 525–528. http://www.nime.org/proceedings/2014/nime2014_292.pdf

[111] Nicolai Marquardt, Johannes Kiemer, and Saul Greenberg. 2010. What Caused That Touch?: Expressive Interaction with a Surface Through Fiduciary-tagged Gloves. In *ACM International Conference on Interactive Tabletops and Surfaces (ITS '10)*. ACM, New York, NY, USA, 139–142. DOI: http://dx.doi.org/10.1145/1936652.1936680

[112] Yasushi Matoba, Toshiki Sato, Nobuhiro Takahashi, and Hideki Koike. 2012. ClaytricSurface: An Interactive Surface with Dynamic Softness Control Capability. In *In Proc. ACM SIGGRAPH'12. Emerging Technologies*. ACM, New York, NY, USA, 6:1–6:1. DOI: http://dx.doi.org/10.1145/2343456.2343462

[113] Matthias Milczynski, Thomas Hermann, Till Bovermann, and Helge Ritter. 2006. A malleable device with applications to sonification-based data exploration.. In *In Proc. ICAD'06. 12th International Conference on Auditory Display*. London, UK, 69–76.

[114] Eduardo Reck Miranda and Marcelo Wanderley. 2006. *New Digital Musical Instruments: Control And Interaction Beyond the Keyboard (Computer Music and Digital Audio Series)*. A-R Editions, Inc., USA.

[115] Geoffrey C. Morris, Sasha Leitman, and Marina Kassianidou. 2004. SillyTone Squish Factory. In *Proceedings of the International Conference on New Interfaces for Musical Expression*. Hamamatsu, Japan, 201–202. http://www.nime.org/proceedings/2004/nime2004_201.pdf

[116] Axel G. E. Mulder and Sidney Fels S. 1998. Sound Sculpting: Manipulating Sound through Virtual Sculpting. In *Proceedings of Western Computer Graphics Symposium 1998*.

[117] Tamotsu Murakami and Naomasa Nakajima. 1994. Direct and Intuitive Input Device for 3-D Shape Deformation. In *Conference Companion on Human Factors in Computing Systems (CHI '94)*. ACM, New York, NY, USA, 233–236. DOI: http://dx.doi.org/10.1145/259963.260449

[118] Tamotsu Murakami and Naomasa Nakajima. 2000. DO-IT: deformable object as input tool for 3-D geometric operation. *Computer-Aided Design* 32, 1 (2000), 5 – 16. DOI: http://dx.doi.org/10.1016/S0010-4485(99)00078-0

[119] Yusuke Nakagawa, Akiya Kamimura, and Yoichiro Kawaguchi. 2012. MimicTile: A Variable Stiffness Deformable User Interface for Mobile Devices. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '12)*. ACM, New York, NY, USA, 745–748. DOI: http://dx.doi.org/10.1145/2207676.2207782

[120] Kosuke Nakajima, Yuichi Itoh, Yusuke Hayashi, Kazuaki Ikeda, Kazuyuki Fujita, and Takao Onoye. 2013. Emoballoon: A balloon-shaped interface recognizing social touch interactions. In *2013 IEEE Virtual Reality (VR)*. 1–4. DOI: http://dx.doi.org/10.1109/VR.2013.6549433

[121] Satoshi Nakamaru, Ryosuke Nakayama, Ryuma Niiyama, and Yasuaki Kakehi. 2017. FoamSense: Design of Three Dimensional Soft Sensors with Porous Materials. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology (UIST '17)*. ACM, New York, NY, USA, 437–447. DOI: http://dx.doi.org/10.1145/3126594.3126666

[122] Vinh P. Nguyen, Sang Ho Yoon, Ansh Verma, and Karthik Ramani. 2014. BendID: Flexible Interface for Localized Deformation Recognition. In *Proceedings of the 2014 ACM International Joint Conference on Pervasive and Ubiquitous Computing (UbiComp '14)*. ACM, New York, NY, USA, 553–557. DOI: http://dx.doi.org/10.1145/2632048.2636092

[123] Jaime Oliver and Mathew Jenkins. 2008. The Silent Drum Controller: A New Percussive Gestural Interface. In *Proceedings of the 2008 International Computer Music Conference (ICMC'08)*. International Computer Music Association, New York, NY, USA. https://quod.lib.umich.edu/i/icmc/bbp2372.2008.118/1

[124] Alex Olwal, Jon Moeller, Greg Priest-Dorman, Thad Starner, and Ben Carroll. 2018. I/O Braid: Scalable Touch-Sensitive Lighted Cords Using Spiraling, Repeating Sensing Textiles and Fiber Optics. In *The 31st Annual ACM Symposium on User Interface Software and Technology Adjunct Proceedings, UIST 2018, Berlin, Germany, October 14-17, 2018*. 203–207. DOI: http://dx.doi.org/10.1145/3266037.3271651

[125] Jifei Ou, Lining Yao, Daniel Tauber, Jürgen Steimle, Ryuma Niiyama, and Hiroshi Ishii. 2013. jamSheets: Thin Interfaces with Tunable Stiffness Enabled by Layer Jamming. In *Proceedings of the 8th International Conference on Tangible, Embedded and Embodied Interaction (TEI '14)*. ACM, New York, NY, USA, 65–72. DOI:http://dx.doi.org/10.1145/2540930.2540971

[126] Dan Overholt. 2001. The MATRIX : A Novel Controller for Musical Expression. In *Proceedings of the International Conference on New Interfaces for Musical Expression*. Seattle, WA, 38–41. http://www.nime.org/proceedings/2001/nime2001_038.pdf

[127] Amanda Parkes, Vincent LeClerc, and Hiroshi Ishii. 2006. Glume: Exploring Materiality in a Soft Augmented Modular Modeling System. In *CHI '06 Extended Abstracts on Human Factors in Computing Systems (CHI EA '06)*. ACM, New York, NY, USA, 1211–1216. DOI: http://dx.doi.org/10.1145/1125451.1125678

[128] Patrick Parzer, Adwait Sharma, Anita Vogl, Jürgen Steimle, Alex Olwal, and Michael Haller. 2017. SmartSleeve: Real-time Sensing of Surface and Deformation Gestures on Flexible, Interactive Textiles, Using a Hybrid Gesture Detection Pipeline. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology (UIST '17)*. ACM, New York, NY, USA, 565–577. DOI: http://dx.doi.org/10.1145/3126594.3126652

[129] Joshua Peschke, Fabian Göbel, Thomas Gründer, Mandy Keck, Dietrich Kammer, and Rainer Groh. 2012. DepthTouch: An Elastic Surface for Tangible Computing. In *Proceedings of the International Working Conference on Advanced Visual Interfaces (AVI '12)*. ACM, New York, NY, USA, 770–771. DOI: http://dx.doi.org/10.1145/2254556.2254706

[130] David Phelan. 2018. Forget Samsung Galaxy X. Apple Is Developing A Foldable iPhone For 2020, Analyst Says. Forbes. (23 March 2018).

[131] Ben Piper, Carlo Ratti, and Hiroshi Ishii. 2002. Illuminating Clay: A 3-D Tangible Interface for Landscape Analysis. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '02)*. ACM, New York, NY, USA, 355–362. DOI: http://dx.doi.org/10.1145/503376.503439

[132] Parinya Punpongsanon, Daisuke Iwai, and Kosuke Sato. 2013. DeforMe: Projection-based Visualization of Deformable Surfaces Using Invisible Textures. In *SIGGRAPH Asia 2013 Emerging Technologies (SA '13)*. ACM, New York, NY, USA, Article 8, 3 pages. DOI: http://dx.doi.org/10.1145/2542284.2542292

[133] Isabel P. S. Qamar, Rainer Groh, David Holman, and Anne Roudaut. 2018. HCI Meets Material Science: A Literature Review of Morphing Materials for the Design of Shape-Changing Interfaces. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. ACM, New York, NY, USA, Article 374, 23 pages. DOI: http://dx.doi.org/10.1145/3173574.3173948

[134] Raf Ramakers, Johannes Schöning, and Kris Luyten. 2014. Paddle: Highly Deformable Mobile Devices with Physical Controls. In *In Proc. CHI'14. Conference on Human Factors in Computing Systems*. ACM, New York, NY, USA, 2569–2578. DOI: http://dx.doi.org/10.1145/2556288.2557340

[135] Majken K. Rasmussen, Esben W. Pedersen, Marianne G. Petersen, and Kasper Hornbæk. 2012. Shape-changing Interfaces: A Review of the Design Space and Open Research Questions. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '12)*. ACM, New York, NY, USA, 735–744. DOI: http://dx.doi.org/10.1145/2207676.2207781

[136] Majken K. Rasmussen, Giovanni M. Troiano, Marianne G. Petersen, Jakob G. Simonsen, and Kasper Hornbæk. 2016. Sketching Shape-changing Interfaces: Exploring Vocabulary, Metaphors Use, and Affordances. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. ACM, New York, NY, USA, 2740–2751. DOI: http://dx.doi.org/10.1145/2858036.2858183

[137] Carlo Ratti, Yao Wang, Ben Piper, Hiroshi Ishii, and Assaf Biderman. 2004. PHOXEL-SPACE: An Interface for Exploring Volumetric Data with Physical Voxels. In *Proceedings of the 5th Conference on Designing Interactive Systems: Processes, Practices, Methods, and Techniques (DIS '04)*. ACM, New York, NY, USA, 289–296. DOI: http://dx.doi.org/10.1145/1013115.1013156

[138] Michael Reed. 2009. Prototyping Digital Clay As an Active Material. In *Proceedings of the 3rd International Conference on Tangible and Embedded Interaction (TEI '09)*. ACM, New York, NY, USA, 339–342. DOI: http://dx.doi.org/10.1145/1517664.1517733

[139] Christian Rendl, David Kim, Sean Fanello, Patrick Parzer, Christoph Rhemann, Jonathan Taylor, Martin Zirkl, Gregor Scheipl, Thomas Rothländer, Michael Haller, and Shahram Izadi. 2014. FlexSense: A Transparent Self-sensing Deformable Surface. In *In Proc. UIST'14 ACM Symposium on User Interface Software and Technology*. ACM, New York, NY, USA, 129–138. DOI: http://dx.doi.org/10.1145/2642918.2647405

[140] Simon Robinson, Céline Coutrix, Jennifer Pearson, Juan Rosso, Matheus Fernandes Torquato, Laurence Nigay, and Matt Jones. 2016. Emergeables: Deformable Displays for Continuous Eyes-Free Mobile Interaction. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. ACM, New York, NY, USA, 3793–3805. DOI: http://dx.doi.org/10.1145/2858036.2858097

[141] James Rogerson. 2018. Samsung Galaxy X: the story of Samsung's foldable phone so far. TechRadar. (10 Sep 2018).

[142] Anne Roudaut, Abhijit Karnik, Markus Löchtefeld, and Sriram Subramanian. 2013. Morphees: Toward High "Shape Resolution" in Self-actuated Flexible Mobile Devices. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '13)*. ACM, New York, NY, USA, 593–602. DOI: http://dx.doi.org/10.1145/2470654.2470738

[143] Deepak Ranjan Sahoo, Kasper Hornbæk, and Sriram Subramanian. 2016. TableHop: An Actuated Fabric Display Using Transparent Electrodes. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. ACM, New York, NY, USA, 3767–3780. DOI: http://dx.doi.org/10.1145/2858036.2858544

[144] Mirza Saquib Sarwar, Yuta Dobashi, Claire Preston, Justin K. M. Wyss, Shahriar Mirabbasi, and John David Wyndham Madden. 2017. Bend, stretch, and touch: Locating a finger on an actively deformed transparent sensor array. *Science Advances* 3, 3 (2017). DOI:http://dx.doi.org/10.1126/sciadv.1602200

[145] Toshiki Sato, Haruko Mamiya, Hideki Koike, and Kentaro Fukuchi. 2009. PhotoelasticTouch: Transparent Rubbery Tangible Interface Using an LCD and Photoelasticity. In *Proceedings of the 22Nd Annual ACM Symposium on User Interface Software and Technology (UIST '09)*. ACM, New York, NY, USA, 43–50. DOI: http://dx.doi.org/10.1145/1622176.1622185

[146] Toshiki Sato, Jefferson Pardomuan, Yasushi Matoba, and Hideki Koike. 2014. ClaytricSurface: An Interactive Deformable Display with Dynamic Stiffness Control. *IEEE Computer Graphics and Applications* 34, 3 (May 2014), 59–67. DOI: http://dx.doi.org/10.1109/MCG.2014.39

[147] Matthieu Savary, Diemo Schwarz, and Denis Pellerin. 2012. DIRTI —Dirty Tangible Interfaces. In *Proceedings of the International Conference on New Interfaces for Musical Expression*. University of Michigan, Ann Arbor, Michigan. http://www.nime.org/proceedings/2012/nime2012_212.pdf

[148] Vlad Savov. 2019. Huawei's Mate X foldable phone is a thinner 5G rival to the Galaxy Fold - The Verge. http://tinyurl.com/yxqjjv7r. (2019).

[149] Hideyuki Sawada, Naoyuki Onoe, and Shuji Hashimoto. 1997. Sounds in Hands: A Sound Modifier Using Datagloves and Twiddle Interface. In *Proceedings of the 1997 International Computer Music Conference (ICMC'97)*. ICMA, San Francisco, CA, USA. http://hdl.handle.net/2027/spo.bbp2372.1997.082

[150] Matthew Schmidtbauer, Samuel Johnson, Jeffrey Jalkio, and AnnMarie Thomas. 2012. Squishy Circuits As a Tangible Interface. In *CHI '12 Extended Abstracts on Human Factors in Computing Systems (CHI EA '12)*. ACM, New York, NY, USA, 2111–2116. DOI: http://dx.doi.org/10.1145/2212776.2223761

[151] Martin Schmitz, Jürgen Steimle, Jochen Huber, Niloofar Dezfuli, and Max Mühlhäuser. 2017. Flexibles: Deformation-Aware 3D-Printed Tangibles for Capacitive Touchscreens. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17)*. ACM, New York, NY, USA, 1001–1014. DOI:http://dx.doi.org/10.1145/3025453.3025663

[152] Carsten Schwesig, Ivan Poupyrev, and Eijiro Mori. 2004. Gummi: A Bendable Computer. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '04)*. ACM, New York, NY, USA, 263–270. DOI: http://dx.doi.org/10.1145/985692.985726

[153] Orit Shaer and Eva Hornecker. 2010. 2010. Tangible User Interfaces: Past, Present, and Future Directions. *Found. Trends Hum.-Comput. Interact.* 3, 1–2 (2010), 1–137. DOI:http://dx.doi.org/10.1561/1100000026

[154] Yuebo Shen, Keqin Dou, and Jiawei Gu. 2013. RoCuModel: An Iterative Tangible Modeling System. In *Proceedings of the 8th International Conference on Tangible, Embedded and Embodied Interaction (TEI '14)*. ACM, New York, NY, USA, 73–76. DOI: http://dx.doi.org/10.1145/2540930.2540960

[155] Jia Sheng, Ravin Balakrishnan, and Karan Singh. 2006. An Interface for Virtual 3D Sculpting via Physical Proxy. In *In Proc. GRAPHITE'06. 4th International Conference on Computer Graphics and Interactive Techniques in Australasia and Southeast Asia*. ACM, New York, NY, USA, 213–220. DOI: http://dx.doi.org/10.1145/1174429.1174467

[156] Paden Shorey and Audrey Girouard. 2017. Bendtroller: An Exploration of In-Game Action Mappings with a Deformable Game Controller. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17)*. ACM, New York, NY, USA, 1447–1458. DOI: http://dx.doi.org/10.1145/3025453.3025463

[157] Eric Singer. 2003. Sonic Banana: A Novel Bend-Sensor-Based MIDI Controller. In *Proceedings of the International Conference on New Interfaces for Musical Expression*. Montreal, Canada, 220–221. http://www.nime.org/proceedings/2003/nime2003_220.pdf

[158] Ronit Slyper, Ivan Poupyrev, and Jessica Hodgins. 2011. Sensing Through Structure: Designing Soft Silicone Sensors. In *Proceedings of the Fifth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '11)*. ACM, New York, NY, USA, 213–220. DOI: http://dx.doi.org/10.1145/1935701.1935744

[159] Ross T. Smith, Bruce H. Thomas, and Wayne Piekarski. 2008. Digital Foam Interaction Techniques for 3D Modeling. In *Proceedings of the 2008 ACM Symposium on Virtual Reality Software and Technology (VRST '08)*. ACM, New York, NY, USA, 61–68. DOI: http://dx.doi.org/10.1145/1450579.1450592

[160] Charles Spence. 2011. Crossmodal correspondences: A tutorial review. *Attention, Perception, & Psychophysics* 73, 4 (01 May 2011), 971–995. DOI: http://dx.doi.org/10.3758/s13414-010-0073-7

[161] M. A. Srinivasan and R. H. LaMotte. 1995. Tactual discrimination of softness. *Journal of Neurophysiology* 73, 1 (1995), 88–101. DOI: http://dx.doi.org/10.1152/jn.1995.73.1.88

[162] Jürgen Steimle, Hrvoje Benko, Alvaro Cassinelli, Hiroshi Ishii, Daniel Leithinger, Pattie Maes, and Ivan Poupyrev. 2013a. Displays take new shape: an agenda for future interactive surfaces. In *CHI '13 Extended Abstracts on Human Factors in Computing Systems (CHI EA '13)*. ACM, New York, NY, USA, 3283–3286. DOI:http://dx.doi.org/10.1145/2468356.2479667

[163] Jürgen Steimle, Andreas Jordt, and Pattie Maes. 2013b. Flexpad: Highly Flexible Bending Interactions for Projected Handheld Displays. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '13)*. ACM, New York, NY, USA, 237–246. DOI: http://dx.doi.org/10.1145/2470654.2470688

[164] Steven E. Stemler. 2015. *Content Analysis*. American Cancer Society, 1–14. DOI: http://dx.doi.org/10.1002/9781118900772.etrds0053

[165] Paul Strohmeier, Juan Pablo Carrascal, Bernard Cheng, Margaret Meban, and Roel Vertegaal. 2016. An Evaluation of Shape Changes for Conveying Emotions. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. ACM, New York, NY, USA, 3781–3792. DOI: http://dx.doi.org/10.1145/2858036.2858537

[166] Miriam Sturdee and Jason Alexander. 2018. Analysis and Classification of Shape-Changing Interfaces for Design and Application-based Research. *ACM Comput. Surv.* 51, 1, Article 2 (jan 2018), 32 pages. DOI: http://dx.doi.org/10.1145/3143559

[167] Yuta Sugiura, Masahiko Inami, and Takeo Igarashi. 2012. A Thin Stretchable Interface for Tangential Force Measurement. In *Proceedings of the 25th Annual ACM Symposium on User Interface Software and Technology (UIST '12)*. ACM, New York, NY, USA, 529–536. DOI: http://dx.doi.org/10.1145/2380116.2380182

[168] Yuta Sugiura, Gota Kakehi, Anusha Withana, Calista Lee, Daisuke Sakamoto, Maki Sugimoto, Masahiko Inami, and Takeo Igarashi. 2011. Detecting Shape Deformation of Soft Objects Using Directional Photoreflectivity Measurement. In *Proceedings of the 24th Annual ACM Symposium on User Interface Software and Technology (UIST '11)*. ACM, New York, NY, USA, 509–516. DOI: http://dx.doi.org/10.1145/2047196.2047263

[169] Koray Tahiroğlu, Thomas Svedström, Valtteri Wikström, Simon Overstall, Johan Kildal, and Teemu Ahmaniemi. 2014. SoundFLEX: Designing Audio to Guide Interactions with Shape-Retaining Deformable Interfaces. In *Proceedings of the 16th International Conference on Multimodal Interaction (ICMI '14)*. ACM, New York, NY, USA, 267–274. DOI: http://dx.doi.org/10.1145/2663204.2663278

[170] Dominique Tan, Maciej Kumorek, Andres A. Garcia, Adam Mooney, and Derek Bekoe. 2015. Projectagami: A Foldable Mobile Device with Shape Interactive Applications. In *Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems (CHI EA '15)*. ACM, New York, NY, USA, 1555–1560. DOI: http://dx.doi.org/10.1145/2702613.2732801

[171] Aneesh P. Tarun, Peng Wang, Audrey Girouard, Paul Strohmeier, Derek Reilly, and Roel Vertegaal. 2013. PaperTab: an electronic paper computer with multiple large flexible electrophoretic displays. In *CHI '13 Extended Abstracts on Human Factors in Computing Systems (CHI EA '13)*. ACM, New York, NY, USA, 3131–3134. DOI: http://dx.doi.org/10.1145/2468356.2479628

[172] Giovanni Maria Troiano, Esben Warming Pedersen, and Kasper Hornbæk. 2014. User-defined Gestures for Elastic, Deformable Displays. In *In Proc. AVI'14 International Working Conference on Advanced Visual Interfaces*. ACM, New York, NY, USA, 1–8. DOI: http://dx.doi.org/10.1145/2598153.2598184 00000.

[173] Giovanni Maria Troiano, Esben Warming Pedersen, and Kasper Hornbæk. 2015. Deformable Interfaces for Performing Music. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*. ACM, New York, NY, USA, 377–386. DOI: http://dx.doi.org/10.1145/2702123.2702492

[174] Giovanni Maria Troiano, John Tiab, and Youn-Kyung Lim. 2016. SCI-FI: Shape-Changing Interfaces, Future Interactions. In *Proceedings of the 9th Nordic Conference on Human-Computer Interaction (NordiCHI '16)*. ACM, New York, NY, USA, Article 45, 10 pages. DOI:http://dx.doi.org/10.1145/2971485.2971489

[175] Yuta Ujiie, Wakayo Yamashita, Waka Fujisaki, So Kanazawa, and Masami K Yamaguchi. 2018. Crossmodal association of auditory and visual material properties in infants. *Scientific reports* 8, 1 (2018), 9301.

[176] John Underkoffler and Hiroshi Ishii. 1999. Urp: A Luminous-tangible Workbench for Urban Planning and Design. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '99)*. ACM, New York, NY, USA, 386–393. DOI: http://dx.doi.org/10.1145/302979.303114

[177] Nirzaree Vadgama and Jürgen Steimle. 2017. Flexy: Shape-Customizable, Single-Layer, Inkjet Printable Patterns for 1D and 2D Flex Sensing. In *Proceedings of the Eleventh International Conference on Tangible, Embedded, and Embodied Interaction (TEI '17)*. ACM, New York, NY, USA, 153–162. DOI: http://dx.doi.org/10.1145/3024969.3024989

[178] Karen Vanderloock, Vero Vanden Abeele, Johan A.K. Suykens, and Luc Geurts. 2013. The Skweezee System: Enabling the Design and the Programming of Squeeze Interactions. In *In Proc. UIST'13. Annual ACM Symposium on User Interface Software and Technology*. ACM, New York, NY, USA, 521–530. DOI: http://dx.doi.org/10.1145/2501988.2502033

[179] Marynel Vázquez, Eric Brockmeyer, Ruta Desai, Chris Harrison, and Scott E. Hudson. 2015. 3D Printing Pneumatic Device Controls with Variable Activation Force Capabilities. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*. ACM, New York, NY, USA, 1295–1304. DOI: http://dx.doi.org/10.1145/2702123.2702569

[180] Anita Vogl, Patrick Parzer, Teo Babic, Joanne Leong, Alex Olwal, and Michael Haller. 2017. StretchEBand: Enabling Fabric-based Interactions Through Rapid Fabrication of Textile Stretch Sensors. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17)*. ACM, New York, NY, USA, 2617–2627. DOI: http://dx.doi.org/10.1145/3025453.3025938

[181] Florian Vogt, Timothy Chen, Reynald Hoskinson, and Sidney Fels. 2004. A malleable surface touch interface. In *In Proc. ACM SIGGRAPH'04. Sketches*. Ronen Barzel (Ed.). ACM, New York, NY, USA, 36–. DOI: http://dx.doi.org/10.1145/1186223.1186268

[182] Akira Wakita, Akito Nakano, and Nobuhiro Kobayashi. 2011a. Programmable Blobs: A Rheologic Interface for Organic Shape Design. In *Proceedings of the Fifth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '11)*. ACM, New York, NY, USA, 273–276. DOI: http://dx.doi.org/10.1145/1935701.1935760

[183] Akira Wakita, Akito Nakano, and Michihiko Ueno. 2011b. SMAAD surface: A tangible interface for smart material aided architectural design. In *Proceedings of the 16th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2011)*. 355–364.

[184] X. Wang and A. D. Cheok. 2011. ClayStation: A Mixed Reality Gaming Platform Supporting Playful Learning for Children. In *Proceedings of the 8th International Conference on Advances in Computer Entertainment Technology (ACE '11)*. ACM, New York, NY, USA, Article 69, 2 pages. DOI: http://dx.doi.org/10.1145/2071423.2071509

[185] Kristen Warren, Jessica Lo, Vaibhav Vadgama, and Audrey Girouard. 2013. Bending the Rules: Bend Gesture Classification for Flexible Displays. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '13)*. ACM, New York, NY, USA, 607–610. DOI: http://dx.doi.org/10.1145/2470654.2470740

[186] Tom Warren. 2019. Samsung's foldable phone is the $1,980 Galaxy Fold - The Verge. http://tinyurl.com/y4powub3. (2019).

[187] Chihiro Watanabe, Alvaro Cassinelli, Yoshihiro Watanabe, and Masatoshi Ishikawa. 2014. Generic Method for Crafting Deformable Interfaces to Physically Augment Smartphones. In *CHI '14 Extended Abstracts on Human Factors in Computing Systems (CHI EA '14)*. ACM, New York, NY, USA, 1309–1314. DOI: http://dx.doi.org/10.1145/2559206.2581307

[188] Eri Watanabe, Yuta Hanzawa, and Masa Inakage. 2007. Clay Tone: A Music System Using Clay for User Interaction. In *In SIGGRAPH'07 Posters*. ACM, New York, NY, USA. DOI: http://dx.doi.org/10.1145/1280720.1280890

[189] Yoshihiro Watanabe, Alvaro Cassinelli, Takashi Komuro, and Masatoshi Ishikawa. 2008. The deformable workspace: A membrane between real and virtual space. In *2008 3rd IEEE International Workshop on Horizontal Interactive Human Computer Systems*. 145–152. DOI: http://dx.doi.org/10.1109/TABLETOP.2008.4660197

[190] Martin Weigel and Jürgen Steimle. 2017. DeformWear: Deformation Input on Tiny Wearable Devices. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 1, 2, Article 28 (jun 2017), 23 pages. DOI: http://dx.doi.org/10.1145/3090093

[191] Gil Weinberg. 2002. Playpens, Fireflies and Squeezables: New Musical Instruments for Bridging the Thoughtful and the Joyful. *Leonardo Music Journal* 12 (2002), 43–51. DOI: http://dx.doi.org/10.1162/096112102762295133

[192] Gil Weinberg and Seum-Lim Gan. 2001. The Squeezables: Toward an Expressive and Interdependent Multi-player Musical Instrument. *Computer Music Journal* 25, 2 (2001), 37–45. DOI: http://dx.doi.org/10.1162/014892601750302570

[193] Gili Weinberg, Maggie Orth, and Peter Russo. 2000. The Embroidered Musical Ball: A Squeezable Instrument for Expressive Performance. In *CHI '00 Extended Abstracts on Human Factors in Computing Systems (CHI EA '00)*. ACM, New York, NY, USA, 283–284. DOI: http://dx.doi.org/10.1145/633292.633457

[194] Michael Wessely, Theophanis Tsandilas, and Wendy E. Mackay. 2016. Stretchis: Fabricating Highly Stretchable User Interfaces. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology (UIST '16)*. ACM, New York, NY, USA, 697–704. DOI: http://dx.doi.org/10.1145/2984511.2984521

[195] Irmandy Wicaksono and Joseph Paradiso. 2017. FabricKeyboard: Multimodal Textile Sensate Media as an Expressive and Deformable Musical Interface. In *Proceedings of the International Conference on New Interfaces for Musical Expression*. 348–353. http://www.nime.org/proceedings/2017/nime2017_paper0066.pdf

[196] Irmandy Wicaksono, Caroline Rozendo, Runzhou Ye, Jaleesa Trapp, V. Michael Bove Jr., Canan Dagdeviren, and Hiroshi Ishii. 2018. PerForm: Deformable Interface for Exploring Sound Through Shapes. In *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems (CHI EA '18)*. ACM, New York, NY, USA, Article LBW605, 6 pages. DOI: http://dx.doi.org/10.1145/3170427.3188478

[197] Valtteri Wikström, Simon Overstall, Koray Tahiroğlu, Johan Kildal, and Teemu Ahmaniemi. 2013. MARSUI: Malleable Audio-reactive Shape-retaining User Interface. In *CHI '13 Extended Abstracts on Human Factors in Computing Systems (CHI EA '13)*. ACM, New York, NY, USA, 3151–3154. DOI: http://dx.doi.org/10.1145/2468356.2479633

[198] Jacob O. Wobbrock, Meredith Ringel Morris, and Andrew D. Wilson. 2009. User-defined gestures for surface computing. In *In Proc. CHI'09*. ACM, New York, NY, USA, 1083–1092. http://dl.acm.org/citation.cfm?id=1518866

[199] Junichi Yamaoka and Yasuaki Kakehi. 2012. NeonDough: Crafting with Interactive Lighted Clay. In *ACM SIGGRAPH 2012 Posters (SIGGRAPH '12)*. ACM, New York, NY, USA, Article 74, 1 pages. DOI: http://dx.doi.org/10.1145/2342896.2342985

[200] Zi Ye and Hammad Khalid. 2010. Cobra: Flexible Displays for Mobilegaming Scenarios. In *CHI '10 Extended Abstracts on Human Factors in Computing Systems (CHI EA '10)*. ACM, New York, NY, USA, 4363–4368. DOI: http://dx.doi.org/10.1145/1753846.1754154

[201] Sang Ho Yoon, Ke Huo, and Karthik Ramani. 2016. Wearable textile input device with multimodal sensing for eyes-free mobile interaction during daily activities. *Pervasive and Mobile Computing* 33 (2016), 17 – 31. DOI:http://dx.doi.org/https://doi.org/10.1016/j.pmcj.2016.04.008

[202] Sang Ho Yoon, Ke Huo, Yunbo Zhang, Guiming Chen, Luis Paredes, Subramanian Chidambaram, and Karthik Ramani. 2017. iSoft: A Customizable Soft Sensor with Real-time Continuous Contact and Stretching Sensing. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology, UIST 2017, Quebec City, QC, Canada, October 22 - 25, 2017*. 665–678. DOI: http://dx.doi.org/10.1145/3126594.3126654

[203] Sang Ho Yoon, Luis Paredes, Ke Huo, and Karthik Ramani. 2018. MultiSoft: Soft Sensor Enabling Real-Time Multimodal Sensing with Contact Localization and Deformation Classification. *IMWUT* 2, 3 (2018), 145:1–145:21. DOI: http://dx.doi.org/10.1145/3264955

[204] Kyungwon Yun, JunBong Song, Keehong Youn, Sungmin Cho, and Hyunwoo Bang. 2013. ElaScreen: Exploring Multi-dimensional Data Using Elastic Screen. In *CHI '13 Extended Abstracts on Human Factors in Computing Systems (CHI EA '13)*. ACM, New York, NY, USA, 1311–1316. DOI: http://dx.doi.org/10.1145/2468356.2468590

[205] Marc Zadel, Paul Kosek, and Marcelo M. Wanderley. 2003. A Pliable, Inertial Interface. Technical Report. (2003). http://www.idmil.org/projects/pliable_inertial