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Citation: Nakagaki, Ken, Fitzgerald, Daniel, Ma, Zhiyao (John), Vink, Luke, Levine, Daniel et al. 2019. "Inforce: Bi-directional 'Force' Shape Display For Haptic Interaction."

As Published: 10.1145/3294109.3295621

Publisher: ACM

Persistent URL: https://hdl.handle.net/1721.1/138021

Version: Author's final manuscript: final author's manuscript post peer review, without publisher's formatting or copy editing

inFORCE: Bi-directional ‘Force’ Shape Display For Haptic Interaction

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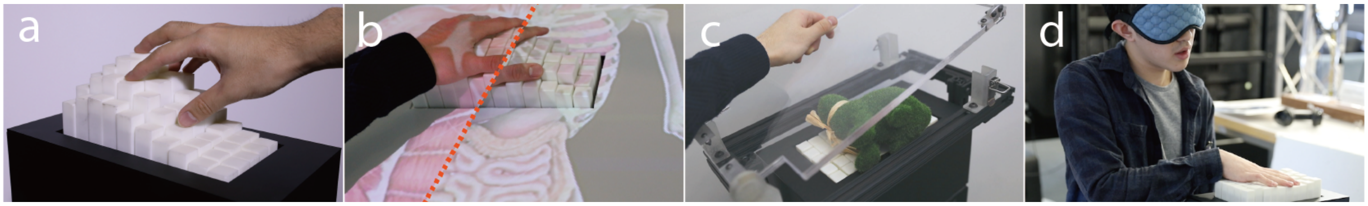

Figure 1. a: *inFORCE* the bi-directional ‘Force’ Shape Display, b: Displaying Multi-layer Medical Data with Dynamic Shape and Haptic Properties c: Scanning Physical Material Compliances, d: User Study for Haptic Perception Evaluation

ABSTRACT

While previously proposed hardware on pin-based shape display has improved various technical aspects, there has been a clear limitation on the haptic quality of variable ‘force’ feedback. In this paper, we explore a novel haptic interaction design space with ‘force’ controlled shape display. Utilizing high performance linear actuators with current reading functionality, we built a 10 x 5 ‘force’ shape display, named *inFORCE*, that can both detect and exert variable force on individual pins. By integrating closed-loop force control, our system can provide real-time variable haptic feedback in response to the way users press the pins. Our haptic interaction design space includes volumetric haptic feedback, material emulation, layer snapping, and friction. Our proposed interaction methods, for example, enables people to “press through” computationally rendered dynamic shapes to understand the internal structure of 3D volumetric information. We also demonstrate a material property capturing functionality. Our technical evaluation and user study assesses the hardware capability and haptic perception through interaction with *inFORCE*. We also discuss application spaces that ‘force’ shape display can be used for.

CCS Concepts

•Human-centered computing → Haptic devices;

Author Keywords

Shape Changing Interfaces; Shape Display; Force Feedback; Haptics

TEI ’19, March 17–20, 2019, Tempe, AZ, USA

DOI: https://doi.org/10.1145/3294109.3295621

INTRODUCTION

Shape Changing Interfaces has been one of the major realms in the field of HCI to physically embody shapes of digital data and dynamically adapt to users and contents [7, 16, 29]. However, various objects including the human body and layers of earth have volumetric structures and material properties cannot be represented only by shape rendering capabilities. While some research in actuated interfaces propose methods to render dynamic material stiffness and other material properties on-top of dynamic shapes, such replicated properties are either only on the surface layer or just homogeneous especially in volumetric layers.

We propose a novel pin-based shape display system which can detect and exert variable force for novel haptic interaction. Haptic interaction includes material property emulation and volumetric data representation. We propose a method to embed haptic effects to the volume of Shape Changing Interfaces as a novel way for users to understand volumetric structural data with multi-material properties mapped within a shape. Such interfaces could help medical students to understand biomedical structures and organ properties, or geo-scientists to understand the varying properties of different layers of the earth by touching and pressing through haptics-effects-encoded shape.

As a proof of concept prototype for the above interactions, we introduce *inFORCE*, a ‘force’ shape display which can detect variable force being applied to each pin and exert variable force on contact hands and objects. Technically, our hardware is composed with an array of linear motors that are faster and stronger than most of the previously proposed shape display hardware [18], which expands the design space of haptic interactions. Our approach takes advantage of Tangible and Shape Changing Interfaces, and extends them to give an extra dimension of haptic effects rendering capability beyond shape by integrating variable force control.

The contributions of this paper include;

- Presenting the haptic interaction design space with the bi-directional 'force' shape display.
- Development of *inFORCE* hardware and software to detect and represent variable force for creating interactive haptic effects.
- Evaluation of the force emulation capability and haptic perceptions of *inFORCE* through a technical evaluation and user study.
- Proposing an application space that benefits from the haptic interaction capability with *inFORCE*.

RELATED WORK

Haptic Interfaces

Various types of haptic feedback devices have been explored to present the sensation of virtual objects [15]. Object properties such as surface texture and heaviness have been reproduced through technical approaches including Vibro-Tactile Feedback [24, 26], or Electro-Stimulation [20, 37].

For kinetic compliance control, haptic devices have made use of various form factors, existing in the form of utensils (pens) styluses[21], grasping gloves[5], fingertip texture feedback[4]. Some of these works explore spatial volumetric data representation [3, 31]. In our work we use a shape-changing interface for its ability to create affordances dynamically and enable users' bare hands to interact with emulated data and material. Additionally, generating precise force control to emulate elastic properties in haptic research is also investigated widely using a closed-loop control system [6]. In part of our haptic effects, we also combine such control system to provide a perception of compliance stiffness, but with the shape display.

Shape Changing Interfaces

While variety types of interfaces have been explored in the research realm of Shape Changing Interfaces [29, 16, 7], recent review paper pointed out that "future shape-changing interfaces should render haptic material properties, in addition to shape alone [1]." Some of previous research in HCI technically addressed this challenge by combining pneumatic actuation with jamming [34, 27, 11], and we apply this dual capability (shape + haptic property) to pin-based shape display systems to explore novel haptic interactions.

Pin-based shape displays have been recently explored widely as a general platform of Shape Changing Interfaces for prototyping a range of interactive applications (e.g. remote communication and dynamic affordances [12]) with a range of technical improvements (e.g. higher resolution with movable base [33] and modular design [14]). Volumetric data representation has been introduced with visually overlaying images on shape display system with AR, but without dynamic haptic or force feedback [19]. *Materiable* aimed to emulate material properties through illusionary haptic perception with an interaction framework of touch sensing and a physics simulation model [23]. While this method was a visually effective way to replicate illusionary material perception using actuators with weak force (<1N) and coarse touch detection (required to be pressed-in at least 5mm to detect touch), the integration of actual force control (<4N) with precise force sensitivity to a pin-based shape display directs to an open research space for exploring human perception through digitally rendered material and novel tangible interaction.

Capturing Material Property

Finally, the scanning material properties itself is also widely explored in the engineering systems for material and body measurements [28, 25]. Our system, by taking the pin-based shape display approach, would be the first system that has capability of both capturing and replicating material property. We explore the new interaction design space enabled with this dual capabilities, through multiple applications including CAD (copy, paste and edit digital material) and body adaptation.

INFORCE - BI-DIRECTIONAL 'FORCE' SHAPE DISPLAY

We aim to expand haptic interaction for pin-based shape display by means of variable force and shape control. Figure 2 shows the design space for haptic tangible interaction with pin-based force shape display, categorized into Haptic Feedback (displaying tactile feedback) and Sensing (capturing physical activity).

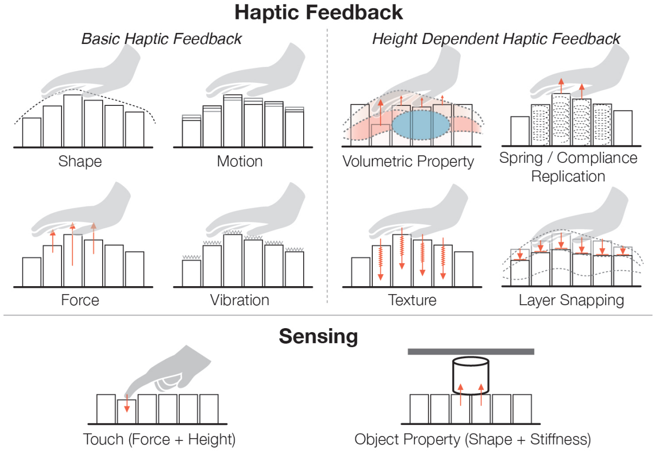

Figure 2. Design Space of *inFORCE* for presenting variable haptic effects and touch / object sensing.

Haptic Feedback

Within Haptic Feedback, *Basic Haptic Feedback* presents a set of primitive haptic properties that 'force' shape displays can present, including not only static shape and motion (which are already common elements in previous shape display research), but also force and vibration. Force is a primitive effect that can be provided when each pin is in contact with user's body. Each pin can have a preset-force that can resist the pressed force until the pressed force becomes higher than the preset-force. Vibration effects simply provide vibration with a desired frequency to provide haptic effects similar to vibro-tactile feedback on each pin.

Height Dependent Haptic Feedback is a type of effect that can be presented based on how users touch or press the display surface. For example, *Volumetric Properties* can be provided, wherein volumetric haptic effects (e.g. stiffness, vibration etc) can be distributed depending on the pin heights when users press into the pins. To replicate the haptic effect of *a spring constant / compliance material*, the force can be gradually increased as users press downwards. *Texture effects* can be rendered by providing vibration + force effects according to the speed and height pins are pressed in [36]. Lastly, *Layer Snapping* is a haptic effect that the surface shape snaps to pre-defined heights when users apply force on the interactive layer. Each layer can have different force thresholds to convey properties (e.g. rigid vs soft) between each layer.

Sensing

For the sensing capability of the 'force' shape display, it can detect human touch - how much force is applied as well as how far the pin is pressed in. It can also recognize object properties - it can measure the weight of objects placed on the pin array, and the shape and stiffness of the object when they are pressed by pins against a flat rigid overhead surface.

DESIGN AND IMPLEMENTATION

The overall system of our prototype is composed of the *inFORCE* shape display itself and a computer that runs a software to control the hardware (Figure 3). The shape display consists of a 10 x 5 array of pins where each pin has a size of 19.2mm square with spacing of 0.8 mm. The overall display size (100x200mm) was chosen to fulfill the size of human hand for demonstrating haptic interaction, while we hope to create larger surfaces in the future.

To demonstrate some of the applications, we included peripheral devices such as projector for mapping images on three sides of the pins (Figure 11), and a USB camera for capturing the appearance of scanning objects (Figure 13). Also for scanning material, we fabricated a scanner attachment counter board for the *inFORCE* system that users can easily place overhead the pin display, so that pin displays can push material to be scanned towards the counter board to capture compliance data (Figure 1c).

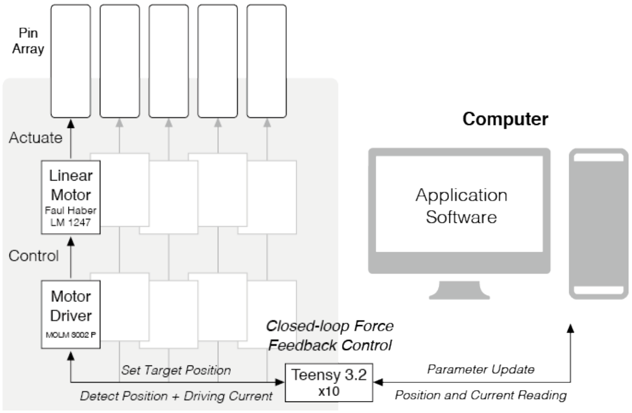

Figure 3. System Overview.

Hardware Design

The hardware of the *inFORCE* shape display contains ten *Teensy 3.2* micro controllers and each micro controller controls five motor drivers through CAN. Each motor driver controls a single linear actuator. We used the "*QUICKSHAFT LM 1247 11 120*" linear actuator and "*MCLM 3002 P*" motor driver both produced by *Faulhaber*. As shown in the Figure 4, motors for one row of pins (10 total) were located on a single layer of a acrylic panel. To compensate for the space and resolution of the hardware, five of them were placed on the bottom of the panel and another five were placed on the top. Metal shafts were used to connect the motor shaft to the pins. Pins were made of white photo-polymer fabricated with a commercial SLA 3D printer. The total weight for the motor to lift was 70g for the top row motors and 95g for the bottom. Each *Teensy* operates at 60Hz to communicate with the motor driver, and the motor driver has the control frequency of $\leq$ 400kHz.

One of the core technologies incorporated into our implementation is the use of the high performance linear actuator *QUICKSHAFT*. This actuator is composed of a 3-phase self-supporting coil together with 3 hall sensors to offer micro-positioning applications [9]. The designated motor driver has its own PID control for position control when it receives command through CAN from *Teensy* and sends back sensor data including position and drawing current. We used this drawing current data to detect force. According to their datasheet, it is able to generate a continuous force of 3.6N and a peak Force 10.7N, with precision of 120µm and maximum speed of 3.2m/s. Each motor is running with 28V and the current it draws under force resistance is in maximum of 1.2A (the motor driver has the current limit function) resulting in up to 1680W in total.

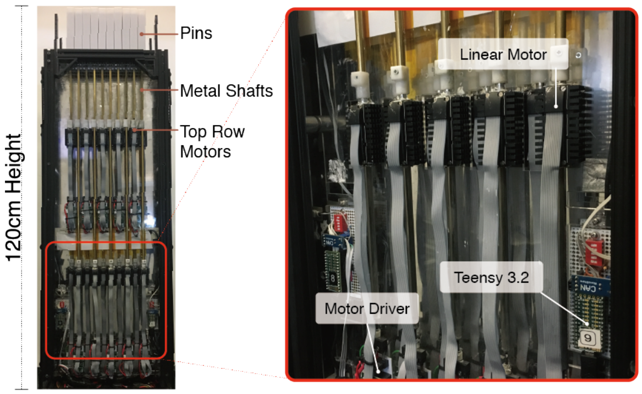

Figure 4. Overall components on a single panel with 10 actuators and zoomed-in view of the top row of motors.

Software

Our software runs on a Windows computer with a frequency of 60Hz and is developed in a C++ environment.

Force Detection

While our motors did not have built-in force sensors, we were able to develop a custom control algorithm to emulate force feedback based on current sensing functionality within the motor driver and position output. Briefly, the current induced in the motor is roughly proportional to the force on the motor: the higher the load on the motor, the higher the induced current in general. However, there are confounding effects that we had to filter out, that we will describe below.

There are two effects that are necessary to be filtered out: additional current due to the movement of the pin, and additional current due to a magnetic pattern present within the motors. The following model suitably governs this relationship:

$$Current \propto (ExternalForce + Movement) \cdot Magnetic$$

Movement describes the additional current required to move the pin, if the pin is moving, and depends on the direction of movement and the location of the pin. If the pin is still, $Movement$=0. $Magnetic$ describes the effect of the magnetic pattern encoded in the shaft of the motor, and is usually a value between 0.9 and 1.1 with no load, depending on the location of the pin. However, this value saturates when there is a load on the motor. Therefore, to form a good estimate of the latent variable Force from the observed variable Current, we must first have good estimates of the $Movement$ and $Magnetic$ variables. We do this during the calibration step, where for each pin, we run a data collection routine where we gather the values of $Movement$ and $Magnetic$. We had to run the calibration several times, once with no weights and two with adding different weight to the pins to characterize the linear proportion of saturation for $Magnetic$. We later use these stored values, in addition to the observed current, to estimate the actual force.

Compliance Material Representation

The algorithm that describes the movement of the pins in response to force is as follows. Each pin height is mapped to a "target force", which is the force that the finger should feel when pressing down on the pin at that height. For example, the target force could linearly map from 0N of force at maximum height to 3N at minimum height, simulating an object following Hooke's Law:

$$TargetForce = SpringConstant \cdot PinHeight \tag{1}$$

A PD control loop then tries to make the force on the pin equal to the target force. If the force on the pin is greater than the target force, the pin moves downwards with velocity proportional to the difference; vice versa, if the force on the pin is smaller than the target force, the pin moves upwards similarly. The kP proportionality constant (in addition to target force) helps control the perceived stiffness of the material. This closed control loop was implemented locally on each Teensy and the software on the computer temporally updates the parameters. Additionally, we developed a control system for an overall shape behavior in response to touch deformation similar to the one proposed in [23].

Rendering Height Dependent Haptic Feedback

The method of creating the dynamic haptic effects is briefly covered below:

Material Emulation: the pins emulate the stiffness and feel of various materials, using the Material Representation algorithm described above.

Volumetric Property: Different target forces were mapped to pin heights. Users could feel the stiffness distribution by pressing-down on the pins.

Layer Snapping: When pressed at the specified force (sum of the force applied for multiple pins) for that layer, the pins snap down to the next layer. This method can be applied to replicating mechanical systems such as switches and toggles.

Vibration Effects: the pins are able to vibrate at a set frequency by oscillating the height up and down around a middle point. We observed that the oscillation is noticeable up to 30Hz. Additionally, by providing vibration as users press down the pins, we were able to generate a rough texture.

Material Stiffness Scanning

Our method to scan the stiffness properties of a material are as follows. The object is first held in place above the pins by a user. Then, each pin moves upwards until it can detect the object. From then, it moves upwards in increments of predefined distance (we used 2.5mm for our prototype), and gathers the force detected from the material onto the pin. After hitting the limit of current (force load) or maximum height, the data of height-dependent force is stored. This data can directly be used as material emulation data to present the amount of force to provide depending on the distance each pin becomes pressed in. Figure 5 shows the material samples of foam and actual scanned data for each material as a reference. This data was used in a user study.

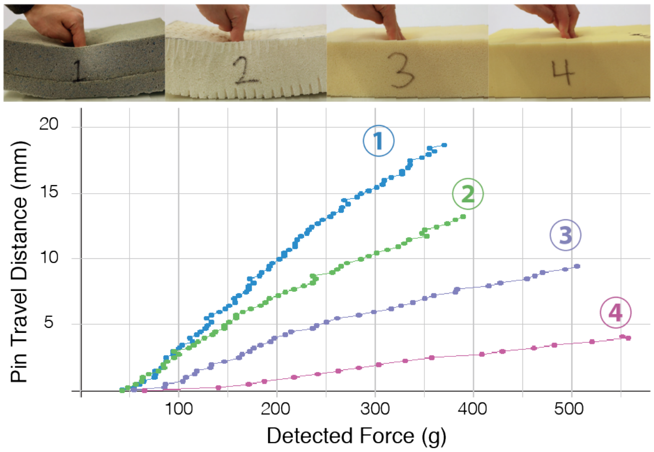

Figure 5. Four scanned foams as material samples (above) and a graph of scanned data results based on a single pin travel distance vs detected force at the relative distance (below). Material 4 is stiffer than 1.

Technical Evaluation for Bi-directional Force Control

We validated bi-directional force control capability of *inFORCE* system. Regarding the force sensing aspect, we first measured the minimum weight the system can detect as external force. We placed weights on each pin (in increments of 10g) and observed the software to start detecting the weight. The average of all data was 57g with SD of 26.04. The resolution of measurement was approximately 0.4g. The maximum weight pins could detect depended on the motor torque as the motor driver had functionality to turn off the motor for a few seconds after drawing too much current. With this, the maximum weight pins could detect was 680g (70g STD) for peak force, and 380g (45g STD) for continuous force.

We also evaluated the force output control capability. As shown in the left of Figure 6, we fixed an analog force gauge above hardware and measured 8 different levels of target force output in a range of 100 - 300g for all 50 pins. Right of Figure 6 shows the results with a graph that shows relationship of target force determined in the system vs actual measured force (average of all 50 pins). The average error was 30.22g.

While the force-controlled shape display itself is novel, these technical evaluation results imply further challenges in accuracy improvements. It could be improved either by in-depth characterization of relationship between force and measured current to update our algorithm. Applying other state-of-the-art force sensing / control methods[6, 17] is another solution.

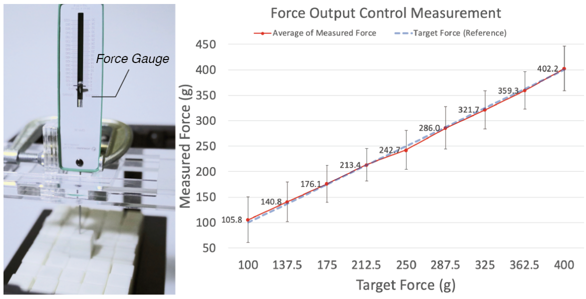

Figure 6. Left: Force output evaluation setup with a force gauge, Right: Graph of the result - target force vs average of measured force.

USER STUDY

In order to evaluate the haptic representation capability of the *inFORCE* system, we conducted three preliminary studies.

Compliance Stiffness - Our first study was conducted to validate the stiffness perception rating based on the material replication algorithm described by Hooke's law in equation 1 where *SpringConstant* was set to 1 of 6 different parameters (0.01, 0.02, 0.04, 0.08, 0.1 and 0.64) that we chose through preliminary adjustments. Due to time constraints, each participant was tested twice for each emulated stiffness (12 trials in total) and we asked them to answer the perceived stiffness in their own scale [8, 35].

Material Comparison - The purpose of this study was to evaluate the haptic replication capability of scanned material compliance properties. We utilized both the captured data and the actual material samples presented in Figure 5. Participants were asked to compare the rendered material on *inFORCE* and actual material through haptic exploration and give a number on how close they are (100 being perfect). Since *inFORCE* is not capable of rendering the surface texture of materials, we prepared a pin display-based haptic filter with the same dimensions as *inFORCE* which can be placed on top of material samples (Figure 7). This filter replicates the compliance force while keeping the surface texture / structure functionally identical to *inFORCE*. Participants were asked to compare four sets of haptic explorations for four different materials (16 total) in random order, and for the closest score they gave in each digitally emulated material they were also asked why it was close and how it could be perfect.

Multi-Layer - Finally, *Multi-Layer* study was conducted to evaluate the volumetric haptic effects distributed in multi-layers as users pressed the pins down. The *Layer Snapping* haptic effect (Figure 2) with multi-layer of flat surface shapes was used in this evaluation. After applying force and snapping to next layer, participants were asked to answer the stiffness value and layer thickness (distance to snap to next layer) they just felt in their own scale. Participants rated a total of 20 layers of stiffness and thickness. The stiffness value and thickness values were generated randomly every time within a range of 130 - 2800g for stiffness, and 5 - 25mm for thickness.

Because the main purpose of all three studies was to evaluate the stiffness, volumetric and material property perception, we set the shape of the surface to be flat by default.

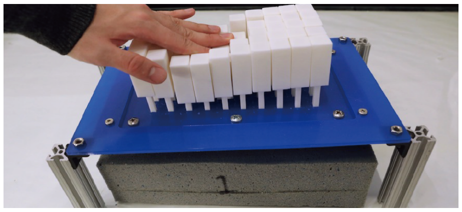

Figure 7. Pin display based-haptic filter replicated with same dimension of *inFORCE* system to use in Material Comparison Study. Materials in Figure 5 are placed below the filter so users can feel the compliance stiffness through pressing the pins.

Procedure and Participants

For all three studies, users were asked to wear an eye mask to remove visual bias and communicate with the experimenters vocally. They were asked to use their dominant hand to press the pins throughout all studies. They were also advised to touch or press the pins in various ways (e.g. with finger tips and palms, or with different speeds and forces). Participants (N = 10, 5 female, 5 male), aged 18-32 (M = 23.78, SD = 5.87) were recruited for these studies and received 15 USD gift cards as compensation. Three studies were conducted in a row which lasted approximately 30 - 45 minutes total, including 3 minutes of break in-between. At the end of the study, they were asked to fill in a short questionnaire about their experiences.

Results and Discussion

Figure 8, 9, and 10 show the results of all three studies respectively. The results of the *Compliance Stiffness* and *Multi-Layer* studies show overall proportional responses relative to the emulated stiffness properties, while the *Material Comparison* showed some unintended results. In the study, for material 4, which was the most rigid material among others, people tended to answer highest closeness score for the correct one. However, participants seemed to mix up three of the other softer material data; many identified replicated materials 1-3 as being closest to the haptic sensation of Material 3. While the material scanning results showed a relatively linear value in Figure 5 for stiffness reading, there can be a problem in the scanning quality to detect more complex material properties such as elasticity - how fast a material pushes back after compression. Some participants reported the big difference between the rendered material and actual material was the speed it comes back to its original shape. Some participants also reported that there was a small oscillation when pins were pressed down in depth, which implies several further improvements on control including calibration, update frequency, and algorithms. Because the softer emulated materials could more easily be pressed down, this can also be the reason Material 1-2 had low scores in closeness. Both these problems can be a challenge for future improvements both in material scanning and emulation. Furthermore, it also suggests that a comparative study would be needed to validate how well people can perceive the closeness between actual material samples with our filter on Figure 7.

In the post-study survey, we asked the question "How well were you able to feel the stiffness / emulated material for the following methods of touching? Pressing with finger tip(s) vs. pressing with a palm" that was to be answered in a 5-point likert scale (5 meaning very good and 1 meaning very poor). The average score for finger tip(s) was 3.5, and palm was 4.1. We assume this was because individual motor was not strong enough when they were strongly poked by finger tip(s) (over 6.8N based on our evaluation), while when using palms the load was distributed over multiple pins so it was harder to press beyond the intended position. We believe adding a mechanical clutch or brake mechanism to individual pins might be one of the solutions for future improvement.

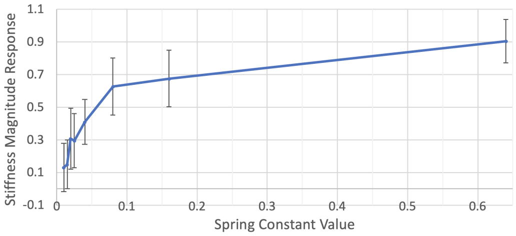

Figure 8. Result of stiffness magnitude response for digitally rendered stiffness with 6 levels of *SpringConstant* values. The error bars represent the standard deviation values.

		Actual Material Samples			
		Material1	Material2	Material3	Material4
Replicated Materials	Material1	64.5 [19.7]	54.1 [18.0]	82.3 [6.5]	46.4 [21.0]
	Material2	47.1 [15.5]	54.1 [20.1]	80.5 [13.0]	50.5 [29.1]
	Material3	45.0 [19.4]	52.5 [16.9]	78.6 [10.7]	61.2 [14.8]
	Material4	39.0 [17.4]	36.8 [15.7]	63.6 [14.5]	85.0 [11.2]

Figure 9. Table of comparison with actual material samples and replicated material data on *inFORCE*. Values are the average scores of closeness ratings from all participants' responses (100 to be perfect closeness.). Values in [ ] represents the standard deviation for each data.

APPLICATION SPACE

We present potential applications that demonstrate the capability of bi-directional force and shape rendering, as well as haptic interaction techniques of the *inFORCE* shape display.

Geological Data Representation

The expressivity of *inFORCE* display can present various kinds of data to present multi-dimensional data including shape and volumetric material data. Geo-science data is one of them. Seismic geo-science data contains multi-layered data with each layer having unique material properties. Geo-scientists commonly view such complex data on screens as layers of section-cut visualized data. It is therefore difficult to comprehensively understand the 3D volumetric layered data and seismic properties. Getting an intuitive understanding for such a spatial and material property is a very important task for a range of fields including the oil and gas domains [13]. For example, as we discussed with oil companies, we learned that geo-scientists need to find a rigid layer of earth to estimate where the oil might be contained. Figure 11 shows an example of a user exploring through different layers of replicated earth seismic data. As a user press in the pins, the rendered shape snaps to different layers of seismic data according to the amount of force the user applies. This force can be variable depending on the geo-property data for each layer, so that the user can intuitively understand both the material property and shape of each layer.

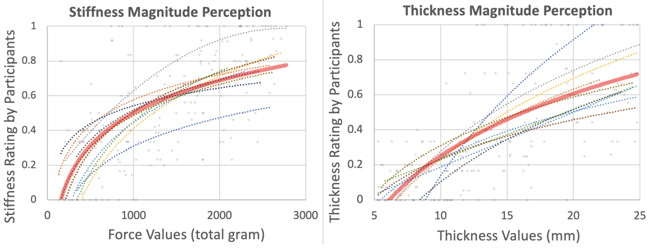

Figure 10. Result of *Multi-Layer* study for stiffness and thickness perception. The thick red line represents the logarithmic trend line of collected responses from all participants, while each dotted-line represents the trend line from each participant's responses.

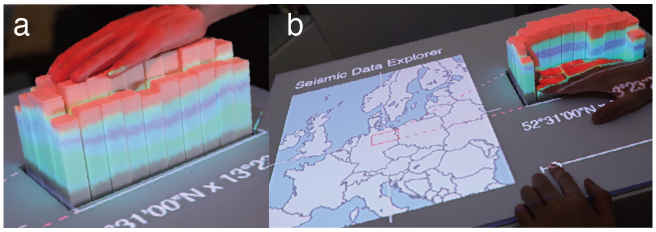

Figure 11. Geoscience Data Exploration (a: Zoomed-in view of earth layers projected on the sides of pins, b: Zoomed-out view of the GeoScience UI for users to choose location to render layer data.)

Medical Data Replication

Another promising field for data representation using *inFORCE* is the medical field, wherein the haptic display can be used to train doctors in the palpation of different parts of the body [38]. Usually when medical students learns the body structure and surgery, they require a cadaver (which can be expensive), large 2D screens (which lacks the tactile sensation) [2], or a static anatomy model (which has limits to dynamically render different shapes and conditions). While similar applications have been presented in the field of haptics and shape changing interfaces [23], the *inFORCE* system allows rendering of depth and force feedback without wearing any device on our body. With the height dependent force feedback capability, a user can experience touching the volumetric body data that can only be perceived when pressing in by certain amount. Haptic perception of a tumor can be replicated when it is presented stiffer as a user pressed replicated body with specific depth, and heart pulse can be replicated by presenting a certain frequency of vibration with specific depth (Figure 12a). Figure 12b shows how *inFORCE* can be used for CRP training which requires specific force and timing. The training can be tracked and evaluated by the system for learning. The scanning functionality of *inFORCE* can be combined with this application scenario, where a female user can scan her own breast and use that data to replicate breast tumor information specific to her own body, to learn the proper way to find a breast tumor.

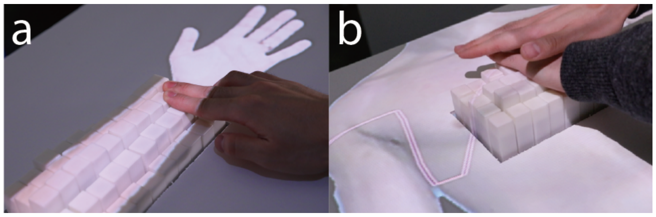

Figure 12. Medical Application Prototype (a: Human arm model that people can feel pulse from only when pressed with appropriate force, b: Chest model for CRP training which requires appropriate force and timing that can be rated by the system.)

CAD Interface for Designing Multi-Material Model

As multi-material fabrication and 3D printing have been rising research topics in recent years, CAD interfaces also need to provide flexibility and intuitiveness for a range of users to easily design their desired shape and material property. Utilizing our system, users can tangibly shape forms, 'paint' material stiffness, and instantly check how the material property feels through their hands and bodies. The volumetric shape rendering capability allow users to modify volumetric material property as well. Additionally, with the material scanning capability, users can take real-world physical objects and materials to bring the physical stiffness in the digital CAD model, and apply the material property in their digital model. This is similar to the ideas of previous work where researchers explored capturing color or shape in the physical environments so that users can create their own digital painting or 3D model [30, 10]. Now, with our system, the material property can be incorporated in computational design for tangibly designing multi-material 3D model 13. Although there is still an interaction design challenge on how to create a UI for such a complex system, it is an exciting research space to tangibly design multi-material 3D models.

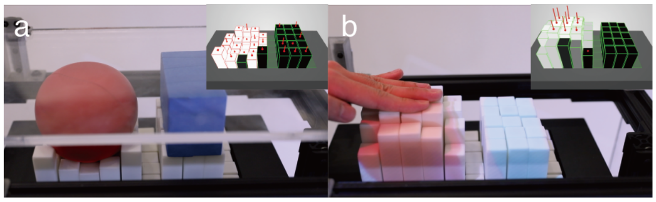

Figure 13. Scanning and replicating Shape, stiffness and appearance of physical materials. Red ball is soft and blue block is rigid. The top right images show the software that represents black pins as detecting rigid material, and white pins as soft material. (a:Scanning material, b: Replicating the captured material.)

Body Adaptation

Based on the dual capability of scanning and rendering material stiffness, the *inFORCE* system has a potential to computationally capture our body data and provide appropriate comfort according to the captured data. This could be the future of furniture where beds, pillow, and chairs can understand our body states and dynamically adapt depending on personal body status and health issues (e.g. injury, pregnancy, etc). While the current system requires a counter plate for object property scanning, a seamless scanning method to capture body states is a primary research challenge for this application domain.

LIMITATION AND FUTURE WORK

While our perception study was purely haptic, the novel interaction method in this paper such as snapping to layer or feeling stiffness through the layer would be interesting to combine with a visual system, just like the projection mapping methods we experimented within our application demonstration. Other types of visual augmentation, such as AR/VR may bring an interesting haptic perception study for multi-modal interaction (e.g. generate visuo-haptic illusion of users penetrating through a larger distance of layer in HMD, to compensate for the limited vertical movement range of the shape display.)

In our user study, we found several limitation of our system and technical challenges to provide intended haptic perception and discussed potential improvements. There are further challenges to enrich and expand other types of haptic properties such as surface texture, or adhesion. Another possible technical improvements include scaling up the size or increasing the resolution of the pin-display. Once it operates at the furniture scale, it may provide body scale interaction in the form of beds or floors, and multi-user interactions in social space [39]. While other researchers work on higher resolution pin display systems [33], it should not be difficult to apply our method to utilize the drawing current on the electrical actuator to generate a force feedback loop. We are excited to see how the interaction quality improves with higher resolution devices. Beyond haptic effects, actuating other materials with force-responsive shape displays is an exciting direction [22, 32]. The strong force may enable advanced object manipulation (e.g. throw, deform, etc), and also the force sensitivity of pins can be used to track the object location and weight.

CONCLUSION

In this paper, we brought force detection and feedback control in pin-based shape displays to explore novel haptic interaction. We introduced the design and implementation of 'force' shape display with closed-loop control software to enable a range of haptic effects. We proposed application spaces to demonstrate how the haptic effects enabled by *inFORCE* could be utilized for volumetric data representation in geoscience and medical fields as well as material scanning and replication in multi-material CAD tools and body adaptation systems. We believe the force interactivity in Shape Changing Interfaces would expand the interaction beyond shape with volumetric materiality and haptic effects to convey rich information to users.

ACKNOWLEDGMENTS

We thank all those who contributed to the hardware development of inFORCE, including: Clark Della Silva, Rebecca Li, Hanjun Li, Daniel Mendelsohn, Baian "Andrew" Chen, Luke Hyman, Yasmine Hassan, Sam Chin, Mary and the "Merry Band of Oliners" (Olin College) and The Norwell High School Robotics Team. We also thank Joanne Leong for reviewing the paper.

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