Materiable: Rendering Dynamic Material Properties in Response to Direct Physical Touch with Shape Changing Interfaces

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ABSTRACT
Shape changing interfaces give physical shapes to digital data so that users can feel and manipulate data with their hands and bodies. However, physical objects in our daily life not only have shape but also various material properties. In this paper, we propose an interaction technique to represent material properties using shape changing interfaces. Specifically, by integrating the multi-modal sensation techniques of haptics, our approach builds a perceptive model for the properties of deformable materials in response to direct manipulation.

As a proof-of-concept prototype, we developed preliminary physics algorithms running on pin-based shape displays. The system can create computationally variable properties of deformable materials that are visually and physically perceivable. In our experiments, users identify three deformable material properties (flexibility, elasticity and viscosity) through direct touch interaction with the shape display and its dynamic movements. In this paper, we describe interaction techniques, our implementation, future applications and evaluation on how users differentiate between specific properties of our system. Our research shows that shape changing interfaces can go beyond simply displaying shape allowing for rich embodied interaction and perceptions of rendered materials with the hands and body.

Author Keywords
Rendered Material Properties; Shape Changing Interface; Physics Simulation; Pin-based Shape Display

ACM Classification Keywords
H.5.2 User Interfaces: Haptic I/O, Interaction Styles

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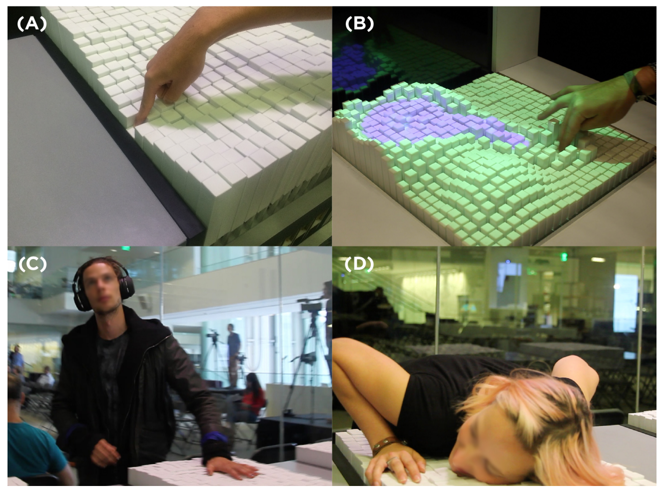

Figure 1. A) Example of a direct input as a distrusted human-material interaction B) Implementation of multiple material properties responding to direct input C)Participant gazes into the distance while trying to feel and identify the rendered material D) A user study participant using their body to feel the rendered material.

INTRODUCTION
Shape changing interfaces have been a recent realm of research in the HCI field [11, 23]. Shapes of 3D digital data or even remote real objects can be rendered and manipulated in physical form, dynamically using various types of shape changing interfaces [8, 18]. While shape, color and animation of objects allows us rich physical and dynamic affordances, our physical world can afford material properties that are yet to be explored by such interfaces. Material properties of shape changing interfaces are currently limited to the material that the interface is constructed with. How can we represent various material properties by taking advantage of shape changing interfaces' capability to allow direct, complex and physical human interactions?

In this paper, we explore methods to represent dynamic human perceivable material properties through shape changing interfaces, where the shape and nature of the material is directly deformed by the user. Specifically, by controlling the shape of interface according to users' direct physical input, we assume that users can perceive of various material properties through physical deformation. To be concise, in this paper we will often refer to '*rendered perceivable properties of deformable materials*' as '*rendered material properties*'. We implemented two main types of material emulations, deformable solid and liquid, using basic physics simulation algorithms on a pin-based shape display in combination with direct physical input detection algorithms (See Figure 1). We propose application's that utilize the display's ability to render multiple material properties at the same time, or to render shapes in response to input. We also conducted preliminary user studies to evaluate how well our technique expresses the given material property and to investigate if users can distinguish specific properties.

RELATED WORK

Various research has been conducted for simulating and representing material properties in multiple fields. In the field of Computer Graphics, researchers have developed algorithms for simulating how objects with different material properties behave differently with external force or gravity [5, 9, 17, 19]. Although every year advancements in their research has shown us astonishingly realistic simulations, they remain limited to the medium of visual feedback, displays and screens.

Towards the goal of representing virtual objects in users' hands, various haptic devices have been proposed to provide the sensation of different material properties [20, 24, 26]. Researchers have utilized haptic systems to replicate elasticity of organs for medical applications [6, 3]. However, works in haptic devices either remain in a flat static surfaces or require additional wearable/hand-held devices that target sensations to specific parts of the body [16].

On the other hand, in some research, the actual properties of physical materials are controlled computationally. This approach enables us to interact with different ways of interaction using any parts of our body. For example, jamming techniques have often been used to dynamically change stiffness of the interface and connect this change to content represented on the jammable material surface with projection [7, 21]. Also, recent 3D printing research enables us to replicate objects to have both various shapes and elasticity by controlling their micro structures [25].

While these research areas always require physical control of force feedback or air pressure, there has been an approach to create illusional haptic sensation by providing visual feedback according to users' action, named "pseudo haptic effect" [14]. With the theory of human perception that we perceive objects not only through haptic feedback but with mix of multi-modal sensory feedback, this technique conveys sensation of virtual objects only by visual effect in reaction to user's motion [2]. For example, this effect is applied to GUI systems where users can perceive changes in rendered textures, such as friction, by observing the way their mouse cursor slows down across the image [13, 27]. The necessity of cross-modal design in haptics to consider not only the touch sense but also other sensory modalities have been emphasized [15].

In contrast to prior work, we introduce a novel interaction technique to represent material properties with shape changing interfaces inspired by pseudo haptic effect, which changes shape according to the direct manipulation from the user. Here, the material is perceived as immediately responding to the users physical interactions and allows for a bi-directional feedback loop, much like one would expect with a real physical materials and common computational devices. In addition, our approach doesn't require any hardware to be attached to the human body. Users can use any part of their body or even other existing physical tools and materials to interact with rendered material properties in order to explore their limitations, feedback and capabilities in the same way one might do so with a real material in the physical world. With this technique, we aim to push the capability of shape changing interfaces beyond shapes even if they are composed with a single material.

RENDERING PERCIEVABLE MATERIAL PROPERTIES OF DEFORMABLE MATERIALS

Physical Material Properties

For the purpose of this paper, we will refer specifically to the mechanical material properties of flexibility, elasticity and viscosity which are percievable through human touch and observation. *Flexibility* is a measure of a solid's ability to be bent or flexed by a given force and is the inverse of stiffness. *Elasticity* is a measure for a materials ability to resist a distorting influence or stress and to return to its original size and shape when the stress is removed. Lastly, the *viscosity* of a fluid is a measure of its resistance to gradual deformation by shear stress or tensile stress. It is informally referred to as the "thickness" of a liquid.

Method of Rendering Dynamic Material Properties

In this paper we attempt to measure the displacement of a user's direct manipulation as touch input, translate this through physics emulations and have the shape changing interface render a dynamic deformable solid or liquid that behaves relative to the calculated physics of this input. One can feel and view the simulation from any angle and direction interactively. As with any real-world material, the user is connected to the simulation through a dynamic physical experience. Our goal is to convey deformable material properties recognizable as actual materials in the physical world even under the constraint of the interface's unvarying materials. Thus, our proposed approach enables shape changing interfaces to represent dynamic shapes and material properties at the same time.

Figure 2 shows the interaction framework we propose. The shape changing interface detects the user's direct physical input using built-in sensors and changes its overall shape with actuators according to a physics emulation that is computed in real time. The deformation is provided to users as both visual and haptic feedback.

To interact with the rendered material on shape changing interfaces, a user can use any part of their body to touch and manipulate the rendered material property as shown in Figure 3. Users can also take advantage of other physical tools or

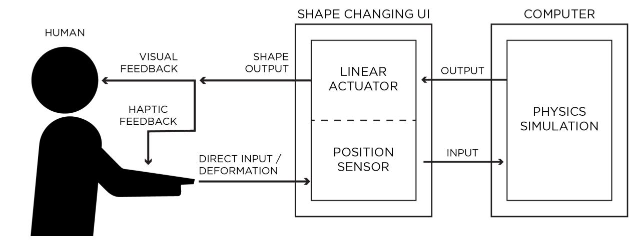

Figure 2. Interaction framework to represent material property using shape changing interfaces.

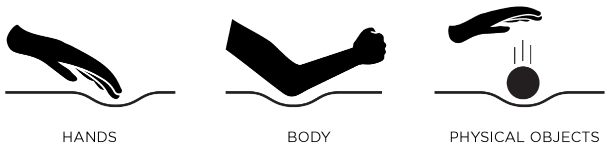

Figure 3. Different ways to feel and interact with the rendered materials we propose.

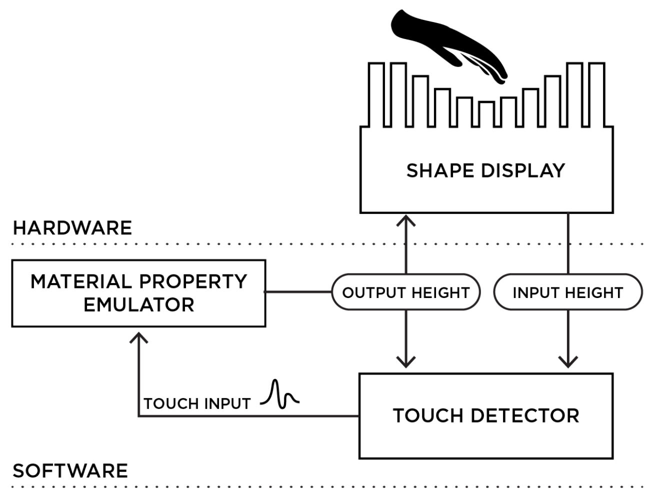

Figure 4. System diagram.

objects to manipulate or test the simulation though this paper does not explore this directly.

TECHNICAL IMPLEMENTATION

As a proof of concept, we implemented a prototype system to represent material properties using two pin-based shape displays.

TRANSFORM system [12] consists of three shape displays, 16×24 pins each, which extend up to 100 mm from the surface, and cover an area of 406×610 mm. Actuation speed is 0.644 m/s and each pin can exert up to 1.08 Newtons. The shape display hardware uses custom Arduino boards that run a PID controller to sense and move the positions polystyrene pins through motorized slide potentiometers (See [8, 12] for details). The TRANSFORM system was used for the user study.

We developed application examples on a smaller shape display [1] consisting of 24×24 actuated pins on a 434×434 mm area. While using similar actuators as the TRANSFORM system, the higher resolution and square form factor was better suited for prototyping more complex applications. This shape display also has a projector mounted to provide graphic feedback on top of the surface of pins.

Our software is written in C++/OpenFrameworks and communicates information with the shape display over USB to RS485. Pin height data is sent and received as a gray-scale image with a 7 bit resolution.

The software for our system can be mainly divided into 2 parts; material property emulator and touch detector (see Figure 4). Certain material properties are simulated in the emulator, then the output shape data is sent to both the shape display and the touch detector. While the shape display renders the shape, it detects the measured height at the same time and passes it to the touch detector. The touch detector detects if each pin is pressed by comparing the output height and measured height. We describe each part in detail below.

Material Property Emulator

The goal of our material property emulator is to loosely approximate the physical behavior of various materials. It was disirable for the material behavior to be realistic in appearance, but it wasn't crucial for the system to be physically accurate. The algorithm presented below outlines the process for emulating two example models, although many more models may be possible in the future. We named our models "Deformable Solid Model" and "Liquid Model." Figure 5 shows the equations used for each model, and Figure 6 gives an overview of the variables we chose.

General Simulation

We represented each material as a two dimensional grid-cell approximation. For each cell, we store its height information as well as its current vertical velocity. Each grid cell in the model maps to a pin on the shape display.

Figure 5 shows a 3 step process the algorithm undergoes for every cell in the model. This process shows how the cell's velocity and height are computed for the next timestep. Here we will give a brief overview of each step in the process.

1. The acceleration for each cell is computed. This acceleration is where we account for any forces on the cell, including spring forces and dampening forces.

2. We perform Euler's Method to integrate the acceleration to get the cell's next velocity, as well as to integrate the cell's velocity to get its next height.

3. Ad-hoc constraints are applied to the cell's height or velocity. This is where each cell may have height or velocity recomputed.

Each mode has its heights rescaled and translated in order to meet the 0 to 255 value range of the shape display's input value for pin height. For input from the touch detector (described later), an impulse value is added to the shape display's touched pin's corresponding cell's velocity. Below, we

	Deformable Solid	Liquid
1 Compute acceleration for each cell	Ai $a_{i,j}(t+\Delta t) = -k\rho_{i,j}(t) - dv_{i,j}(t)$	Aii $a_{i,j}(t+\Delta t) = \frac{c^2}{h^2}(\rho_{i-1,j}+\rho_{i+1,j}+\rho_{i,j-1}+\rho_{i,j+1}-4\rho_{i,j}) - dv_{i,j}(t)$
2 Integrate	Bi, ii $v_{i,j}(t+\Delta t) = v_{i,j}(t) + a_{i,j}(t+\Delta t)\Delta t$ $\rho_{i,j}(t+\Delta t) = \rho_{i,j}(t) + v_{i,j}(t+\Delta t)\Delta t$	
3 Apply ad-hoc constraints	Ci $\rho_{i,j}(t+\Delta t) = b\frac{\rho_{i-1,j}+\rho_{i+1,j}+\rho_{i,j-1}+\rho_{i,j+1}}{4} + s\rho_{i,j}(t+\Delta t)$	Cii No Constraints

Figure 5. Physics algorithm as steps (two-dimensional representation).

Variable	ρ	i,j	a	d	v	t	Δt	k	b	s	c	h
Deformable Solid Implementation	Height	Cell at row i, column j	Acceleration	Dampening Term	Velocity	Time	Time Step Size	Spring Constant	Depression Factor	Elastic Factor	n/a	n/a
Liquid Implementation	Height	Cell at row i, column j	Acceleration	Dampening Term	Velocity	Time	Time Step Size	n/a	n/a	n/a	Wave Speed	Cell Width

Figure 6. Variables used in physics algorithm.

describe how each mode computes its governing forces and which constraints are applied.

Deformable Solid Model

The Deformable Solid Model attempts to emulate the physics behind real world objects like a soft foam or the springs in a mattress. These solids may spring back rapidly after a deformation or slowly return back to their resting state.

The governing forces behind each cell in the deformable solid model is a spring force towards their origin position as well as a dampening force, as shown in Step 1 on Figure 5 Ai. The spring force simply uses Hooke's Law:

$$a = -k\rho$$

Here, the height is the distance from resting state and k is the spring constant. The dampening force pushes against the current velocity scaled by the dampening term d.

With just these forces presented, each cell is simply an over-dampened spring acting independently of the other cells. So in Step 3, we recompute the cell's current height as a linear combination of its current height and the average of its adjacent neighbor cell heights (see Figure 5 Ci). b and s scales the average term and the current cell height term respectively. The averaging term couples cells to their neighbors so that they're softly connected. At the boundaries, for cells at corners and walls, we simply use the average of their surrounding 2 or 3 neighbors.

With the ad-hoc constraint in place, the model simulates a believable foam or mattress surface, depending on how the parameters are tuned. We discuss some of the values we choose for these variables later on in the paper.

Liquid Model

The Liquid Model emulates the physics behind any kind of fluid filled container. Previous work [10] refers to how one can extend the 2D heightfield model to have an adaptive 3D surface with splashing. Since we're limited to a two-dimensional heightfield display, we use a two-dimensional heightfield liquid model.

For the liquid model's governing forces, we employ the Shallow Water Equations and a dampening force. The Shallow Water Equations approximate the full Navier-Stokes equations under the two dimensional height field model [4]. The acceleration for each cell is computed using the density of adjacent cells using the equation seen in Figure 5 Aii. Here, c is the wave speed and h is the cell width. We again included a dampening factor of d, which controls the rate at which waves disappear.

For further stability, we subtract the average density of all cells from each cell density, and constrain each ρ to between -255 and 255. Subtracting the mean keeps the average density at 0, so we can arbitrarily add or remove velocities to cells (such as when a user presses down on a pin) without the total volume of the liquid changing substantially.

Touch Detector

The touch detector algorithm is designed to detect user's physical input by comparing the measured height and the predicted height based on output for each pin. The graph on Figure 7 shows an example of the relationship between input and output height value and a dynamic threshold which is derived from the predicted height for a pin. To predict the height, the delay between when the value is sent and when the pin reaches a given target height is considered to calculate the dynamic threshold. When the actual measured height is not within the range of the dynamic threshold, the algorithm distinguishes it as touch detection. Accordingly, the difference between predicted height and measured height is given to the material emulation algorithm as a force added to rendered materials.

Due to the low positional accuracy of our linear actuators, our prototype initially registered false touches when the output height value changed rapidly. Therefore, we disabled touch

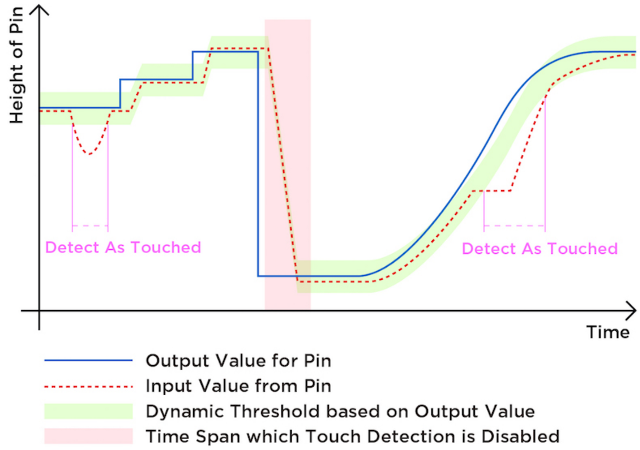

Figure 7. Example Image of Touch Detection Processing.

detection for 0.3 seconds following rapid changes to output values. Touch detection accuracy could be improved with appropriate algorithms and characterizations of individual motors and pin frictions. As a result of our implementation, it took approximately 0.45 seconds for software to detect physical input after pins were actually pressed.

APPLICATIONS

In this section, we demonstrate possible applications that utilize the capability of our technique to render dynamic shapes and material properties at the same time on shape changing interfaces; a pin-based shape display in this case.

Explorative Display

In this application, we introduce our system as a tool for exploring the material properties of objects or anatomical forms through physical manipulation (see Figure 8). In an online furniture store, one might get a sense for how flexible a sofa or mattress might be before purchasing the item. In education, children can explore various anatomical forms of humans or animals to get a sense of their flexibility. They can also understand how materials may combine in chemistry to form viscous materials. Finally in the field of medicine, we can explore different anatomies and render variable flexibility for the materials that make up that anatomy. This can potentially aid practitioners in understanding patients medical data but also the patients themselves who can have concerns explained to them with a rich, physical experience.

Landscape Design + Simulation

Designing complex models such as a landscape or city usually requires the knowledge of complex software and of how different structures and features may interact with each other. With rendered material properties in combination with the ability to directly manipulate 3D shapes, novice users can create and simulate land formations in the same way they might play with the materials usually used to create models (Figure 9). Prior work such as “Illuminated Clay” [22] allowed users to create land forms with the same affordances as a sand pit. Here, rendered material properties allow the combination

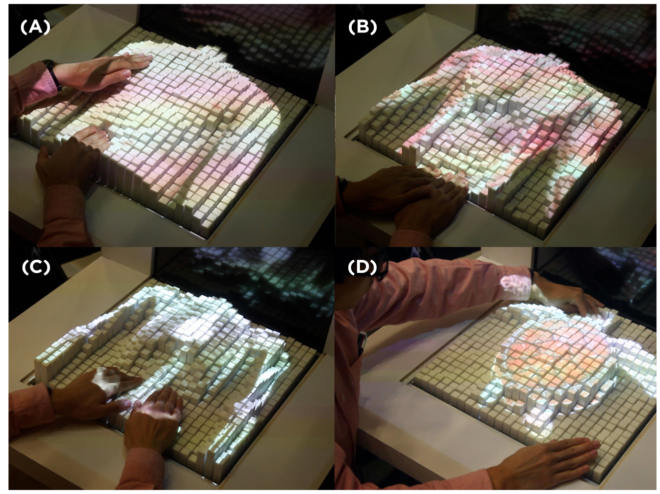

Figure 8. Enhanced experiences with anatomy and biology with juxtaposed rendered material property interactions (A: Body, B:Anatomy , C:Xray and D: Turtle).

of multiple rendered materials that can each be manipulated in different ways. For example, one might create a body of water by deforming a solid behaving material and allowing a viscous material to flow into the container. By extension, a user could also interact with the rendered material to test complex scenarios such as a tsunami or earthquake, invoked by manipulating the interface with considerable force.

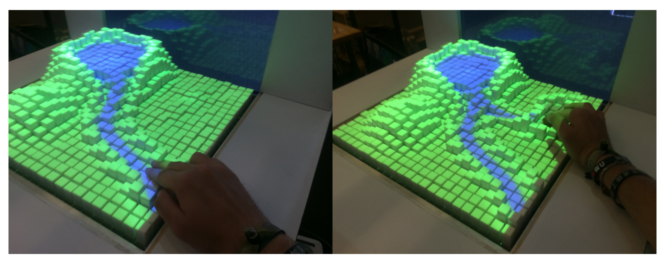

Figure 9. Manipulating and simulating landscapes with flexible, elastic and viscous rendered material properties.

Material Properties as Interaction Cues

In our physical world, we interact differently with materials based on our assumptions of their various properties. These material properties, if emulated in shape changing interfaces, could prove useful for enhancing the way we interact with physical data. For example, CAD applications are split into solid modelers, which involve boolean and parametric operations on “solid” parts while surface modelers usually render the model only has a surface to be manipulated and deformed as a mesh. With the ability to switch between perceived material properties, we envision leveraging human perception to inform the way one may be able to manipulate a form or even to represent the material the form is intended to be constructed with.

Here, the percept of material properties informs the way a user can interact. A more liquid or viscous rendered material property might afford a surface model approach where deformations are direct and local (Figure 10(c)(d)) while a more flexible or elastic rendered material property informs a surface that can be distorted. A more solid body could inform a parametric approach where relationships between parts are structured and deformations global according to guided boolean functions. These more structured and global operations could be performed with gestures or another form of interaction (Figure 10(b)) leaving direct manipulation through physical touch to deformable content. While we see this as exciting in the field of CAD, the same percept of material properties could be used in various other ways we interact with information by applying the metaphor of how “malleable” the information is.

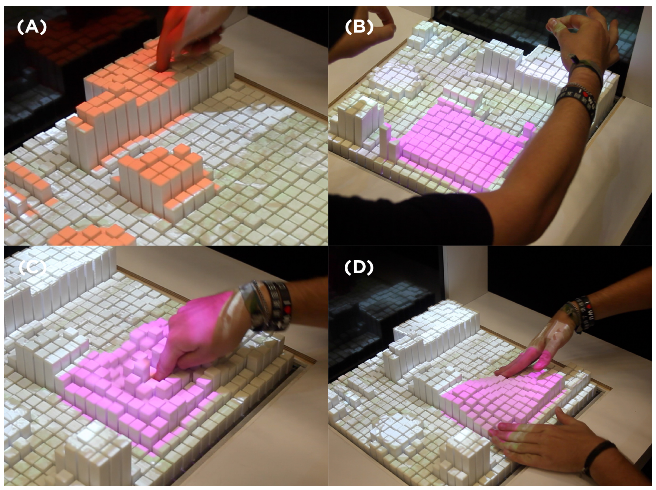

Figure 10. Various material properties inform how a user can manipulate the 3D Data in a city design application (A: Existing rigid buildings that cannot be edited, B: Using gestures to perform global operations on data, C: A viscous material property suggests the body is deformable, D: Keeping the same volume, the form can be manipulated and deformed).

EVALUATION

User Study

We conducted a preliminary user study to evaluate if participants could perceive differences between various rendered materials. 10 participants, from the age of 22 to 35 took place in this user study. There were 5 men and 5 women with no known perception disorders. Our user study was split into a qualitative questioner and a quantitative rating test. For each experiment, users were told to focus on their observations of what they see while interacting with the shape display.

For the user study, we prepared 3 sets of material properties to experiment (flexibility, elasticity, and viscousity) for the participants’ to interact and perceive. The sets of material data we created for experiments were defined based on the variables in equations we described above (see Figure 5). Specifically, we chose to vary the elastic factor s for flexibility and the depression factor b for elasticity both from Deformable Solid Model. The dampening factor d from Luquid Model was selected for experimenting viscousity. We assumed that each variable would affect users’ perception of flexibility, elasticity and viscosity respectively. For each variable, we picked 4 different values and a neutral value which was set as reference point for quantitative experiment. The values were selected based on our prior test that manipulated the variables in our underlying mathematics simulations to create the broadest human perceivable variations. Figure 11 shows the variables and their detailed values used in the experiment.

Evaluated Material Property	Flexibility	Elasticity	Viscousity
Used Model	Deformable Solid Model		Liquid Model
Varied Variable	b	s	d
Values for each Variable ([...] as the neutral value)	0.8, 0.88, [0.92], 0.96, 0.99	0.0005, 0.002, [0.007], 0.01, 0.012	0.0005, 0.001, [0.002], 0.003, 0.005

Figure 11. Table of simulated models and variables used in the evaluation. (See Figure 5 and 6 accordingly)

In both tests we also observed how participants interacted with the rendered material properties. Participants were told they could interact in any way that made sense to them and were shown ways to interact with their hands; using one finger, multiple fingers or palm to press. At the conclusion of both experiments, participants were asked whether they focused on what they saw or felt to discern the rendered material properties of the simulations.

Describe and Identify Material Properties

As for the qualitative questioner, participants were first asked to identify variations of material properties for each emulation. After describing the simulation users were asked to identify one material, if any, that the simulation made them think of.

Rate Material Properties

In the quantitative test, we had users rate perceived material properties between 1-10 (10 to be most flexible, elastic or viscous) for each material properties. Each user tested 3 kinds of material property and 4 different values each as listed in Figure 11, thus 12 times in total. Before rating each property, users had to experience neutral material which was told to be five in ratings. We randomize the order of each material properties that user perceive and rate. In this experiment, users were asked to wear a set of headphones playing white noise to have participants focus on the perception of the simulation and not the loud noises produced by the moving pins.

Results and Discussion

Perception of real world materials

In a qualitative questionnaire experiment, participants were quick to identify rendered material properties in more dynamic simulations. Many participants described the deformable solid implementation with a high depression factor and elastic factor as “trampoline material” and were quick to identify “water” as their best guess for the liquid implementation with low dampening and high wave speed.

Interestingly, despite being told specifically to “observe” the simulation “visually,” all participants described what they “felt” while describing the simulation before them. While we did not test specifically for tactile perception, at the conclusion of the study 8 out of the 10 users stated they were prioritizing their perception of touch over sight when asked to describe, identify and rate the rendered material simulations.

Perceiving Specific Material Properties

Figure 12 shows average scores of participants responses in our quantitative experiment for flexibility, elasticity and viscosity.

We have shown through these tests that we can directly influence perception of material properties by varying our corresponding algorithmic parameters for flexibility, elasticity and viscosity. Most participants vocalized the difficulty of rating flexibility due to the way they had to interact with the shape display pushing with a downwards force which is not an interaction they are used to doing with real world deformable solid materials. Despite this concern with interaction, participants were still able to correctly identify flexibility as a property of the simulation. Viscosity was the most successful property for all participants in terms of the speed of their responses and the accuracy of their rating. We feel this correlates directly to the very active nature of the simulation which depending on the way the participant interacted with it and the level of dampening would have the simulation remain active for a longer period of time than the deformable solid implementation. Preliminary results suggest there is a correlation in the quantitative data we have gathered, however, a more comprehensive user study involving more participants would help to quantify this correlation and further explore specific correlations between perceived material properties and our algorithmic variables.

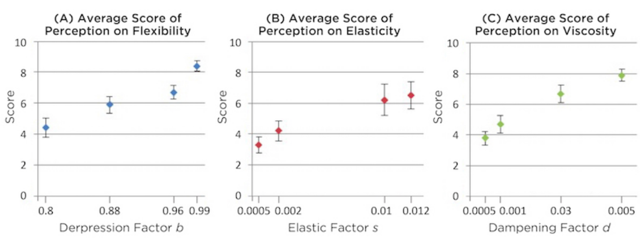

Figure 12. Results of quantitative user study (bars represent standard errors).

LIMITATIONS AND FUTURE WORK

Limitations with Shape Displays

Due to 2.5D movement on current shape displays, some simulated material properties are easier to identify than others. The interactions we have with real world materials are very complex and are not restricted to an array of linear forces. Not all material properties will make sense to simulate on shape displays, for example, any form of gas would be extremely difficult. A deformable solid material is usually grasped to gauge its flexibility, not pushed, however we had to make do with the limitation of the shape displays vertical displacement. Although many people perceived our liquid emulation as water, the rendered liquid can not cover surround the user's hands. Due to this, we are interested in trying different implementations on alternative shape changing interfaces in future work.

We are also limited by the type of sensing and actuators we have built into our current shape displays. We would like to be able to sense the input and vary the output of force as to better match the forces applied to and given back by real world materials. While participants noticed a change in resistance for various materials, this was likely due to the motors moving with them in response to their input and does not accurately represent the forces we would like to represent. Better sensing and actuation would give us the advantage of being able to vary the sensation of stiffness or flexibility more accurately for tactile perception.

Kinetic Relationship with Rendered Materials

The majority of participants in our experiments stated their perception through touch overpowered their perception through observation, notable also in the way many users simply did not look at the shape display while trying to answer our questions. In addition to this, participants were shown how to interact with the simulations using their hands (see Figure 3) and told to interact in whatever way "felt natural." All users, to our surprise, extended this interaction to other parts of their body we had not expected (see Figure 13). While everything in this paper is stated as a simulation, this behavior suggests that directly manipulating a real-world physical form that changes shape, regardless of its underlying computation, for the individual, appears to be a very real and physical experience. Results of both experiments we conducted for this paper point to a tactile perception overpowering that of visual which we believe is due to the fact that participants were directly manipulating a physical object with the added advantage of having a direct connection to their body, the object and space.

Future Work

Although the material emulation algorithms we used in this paper were basic, more advanced material simulation can be applied to our system so that it would improve the variety and quality of rendered material properties. We also believe improving other technical requirements such as response latency and resolution will contribute to the reality of perceived material properties. Additionally, shape display actuators with higher maximum torque would make it possible to render varied force feedback. Although the surface texture on our implementation was polystyrene, improving the resolution of shape display could provide fine tactile feedback. These other aspects of haptics would also improve the quality and variety of rendered haptic material properties accompanying our approach in this paper.

Although our evaluation was only based on users' impressions of material properties, further evaluations based on comparison with actual material are required to understand how rendering material properties with our technique is closer to actual material. We believe it is necessary to have advanced user studies to ask users to compare with actual material. Through such comparative user studies of our system with real material, we could indicate how hardware and software should be improved.

Figure 13. Various ways participants chose to interact with the rendered material properties with their bodies (A: Single finger, B: One palm, C: Multiple fingers, D,E,F: Two palms, G: Two arms, H: Arms and upper body).

We are equally interested in exploring inter-material interaction with real world objects of varying material properties. In our physical world, all material properties are exposed at the interface between two or more materials. We hope to explore how various objects can be manipulated or how they may in turn manipulate our simulations.

Ultimately, we are excited to see how interactions with rendered material properties in tangible interfaces can be used to enhance the human computer interaction experience and bring our experience of computation closer to the ways we so easily interact with our physical world.

CONCLUSION

We have proposed a method to render variable deformable material properties through transformation and direct manipulation using shape changing interfaces. We introduced our prototype with preliminary physics algorithms on a pin-based shape display. The prototype was evaluated through a user test to understand how well users can perceive different rendered material properties, and positive results with some findings in the interaction were observed. In addition, we highlighted a number of application domains and example applications that show how our method can enhance experiences in the fields of education, medicine, landscape design. We envision a future for shape changing interfaces where rendered materials can be recognized by their perceived material properties, directly manipulated and used in applications to enable rich new experiences with digital information.

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