PuPoP: Pop-up Prop on Palm for Virtual Reality

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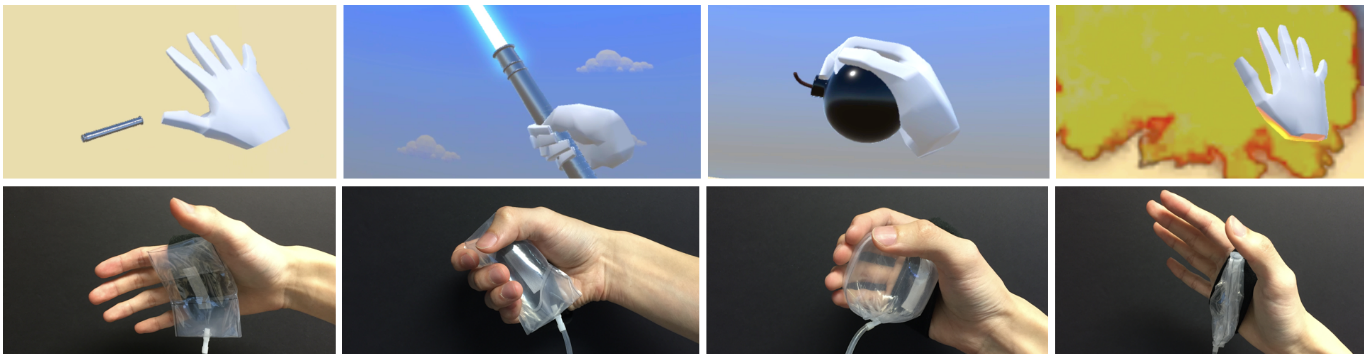

Figure 1. PuPoP is a wearable pneumatic shape-proxy interface for VR capable of popping up to primitive shapes and flattening on the palm. We demonstrate grasping emulation of picking up a virtual Lightsaber with a cylindrical PuPoP and throwing a virtual bomb with a spherical PuPoP.

ABSTRACT
The sensation of being able to feel the shape of an object when grasping it in Virtual Reality (VR) enhances a sense of presence and the ease of object manipulation. Though most prior works focus on force feedback on fingers, the haptic emulation of grasping a 3D shape requires the sensation of touch using the entire hand. Hence, we present *Pop-up Prop on Palm (PuPoP)*, a light-weight pneumatic shape-proxy interface worn on the palm that pops several airbags up with predefined primitive shapes for grasping. When a user's hand encounters a virtual object, an airbag of appropriate shape, ready for grasping, is inflated by way of the use of air pumps; the airbag then deflates when the object is no longer in play. Since PuPoP is a physical prop, it can provide the full sensation of touch to enhance the sense of realism for VR object manipulation. For this paper, we first explored the design and implementation of PuPoP with multiple shape structures. We then conducted two user studies to further understand its applicability. The first study shows that, when in conflict, visual sensation tends to dominate over touch sensation, allowing a prop with a fixed size to represent multiple virtual objects with similar sizes. The second study compares PuPoP with controllers and free-hand manipulation in two VR applications. The results suggest that utilization of dynamically-changing PuPoP, when grasped by users in line with the shapes of virtual objects, enhances enjoyment and realism. We believe that PuPoP is a simple yet effective way to convey haptic shapes in VR.

UIST '18, October 14–17, 2018, Berlin, Germany

DOI: https://doi.org/10.1145/3242587.3242628

Author Keywords
Haptics; Virtual Reality; Airbag; Shape-Proxy

INTRODUCTION
Direct hand manipulation is how humans interact with objects in reality. We grasp objects and perceive their rich haptic feedback to manipulate them [14]. For Virtual Reality (VR), wearable haptic devices have been developed to simulate object grasping using different mechanisms [1, 6, 37, 10, 9]. Although highly mobile, they focus on force feedback on fingers to generate the feeling of firm grasping, the skin contact sensation with the surface of objects during hand manipulation is not provided.

To enable full grasp sensation in VR, an effective solution is to utilize physical proxies [19, 7], *i.e.*, offering users a physical object similar to the virtual one. Previous research works show that physical proxies can significantly increase the sensation of realism [20]. However, the shape, number, and placement of physical proxies [18, 40] depend on the given environment,

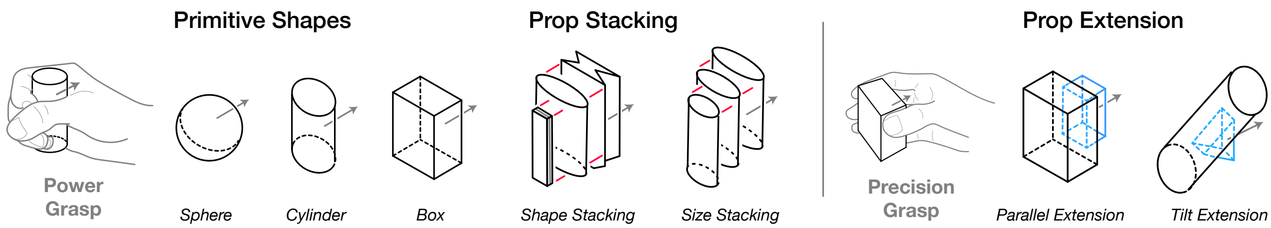

Figure 2. PuPoP design overview (gray arrows indicate the palm direction).

and they are less mobile and responsive when compared to wearable haptic devices.

This paper proposes the concept of a set of always-available physical proxies for generating grasping haptic feedback in VR. We draw inspiration from shape-changing interfaces, especially pneumatic materials [15, 38, 29]. We finally present *Pop-up Prop on Palm (PuPoP)*, a pneumatic shape-proxy interface worn on the palm that “pops up” *i.e.*, inflates using air pumps to appropriate shapes in response to the content conveyed in VR, and then entirely deflates to flat when the virtual object is no longer in play (Figure 1). PuPoP provides the full sensations of grasping objects as it is a physical object acting as a prop. PuPoP is always available for use within the entire VR interaction space because it is mounted on the palm. PuPoP is made of light-weight material making it easy to wear and take off. We believe that PuPoP is a simple yet effective way to enhance the experience of object manipulation in VR.

After consideration of the basic factors of when a human being grasps objects [27], including a power grasp or a precision grasp, along with common VR objects held in hand, we have designed PuPoP with foldable-structure airbags using heat-sealed PE sheets. The airbags are able to form approximate 3D shapes (e.g., a sphere, a cylinder, or a box, etc.) and then to collapse to a nearly flat plane. When the user is about to grasp a virtual object, the airbag of appropriate shape is inflated by air pumps. If the user drops the virtual object, the airbag is deflated. To mount multiple shapes on the palm, we explore ways of stacking the props with different shapes and sizes. To support the pad-opposite type of grasp (e.g., grasping small objects with fingers), we add an additional airbag to lift the prop off the palm. Furthermore, the surfaces of the airbags are affixed with force sensors to detect grasp. The stiffness of an object can be emulated by controlling air flow in response to touch pressure. Last but not least, different shapes of props can be attached to or detached from the palm easily by hook and loop fasteners according to VR applications. Our system incorporates with the HTC VIVE headset and Leap Motion.

We conducted two user studies to evaluate the interface. In the first study, we ascertain the acceptance range of the visual sizes for props with primitive shapes. The results show that while PuPoP consists of props with fixed sizes, it can take advantage of the visual dominance effect to modify the perceived size in VR. In the second study, we compared PuPoP to controllers and free-hand manipulation in two VR applications. The results show that use of PuPoP in a configuration with two sizes of spherical props significantly enhanced the enjoyment of, and object realism in, a ball throwing and catching application. However, the results in regard to use in a painting application, where PuPoP was configured with cylindrical and box-shaped props, did not surpass the performance of controllers. Nonetheless the study’s findings indicate that having dynamically-changing shapes in accordance with the shapes of the virtual objects held in hand did enhance the user experience in VR. The current implementation is limited by inflation time and the stiffness of the props; however this could be compensated for by appropriate VR content design.

The main contributions of this paper are:

1. The concept of a light-weight wearable Pop-up Prop on Palm (PuPoP) apparatus with the capability of inflating and deflating to appropriate physical 3D shapes for VR.
2. The design and implementation of a set of shape structures for PuPoP.
3. A series of user studies to understand visual size acceptance range of PuPoP and evaluate the interface in comparison with controllers and free-hand manipulation in two VR applications.

RELATED WORK

Handheld & Wearable Haptic Devices

In contrast to grounded haptic devices, handheld and wearable haptic devices allow users to move around, expanding their interaction space in VR. Handheld controllers are often used in commercial VR, such as the HTC VIVE controllers; however, they hinder users from manipulating the virtual objects directly. NormalTouch and TextureTouch [5] are controllers that render sensations of surface normal and textures for the fingertip. Since they are designed for the index finger only, they do not allow users to grasp objects.

Wearable haptic devices either emulate cutaneous feedback or kinesthetic feedback, but none of them render both of these categories of sense feedback. Although fingertip haptic devices can emulate cutaneous feedback of object mass, stiffness, and friction using a skin-stretch illusion [32], they cannot emulate the firm grasping of objects. Most haptic exoskeletons for hands [1, 6, 37] provide kinesthetic feedback of rigid grasping using heavy mechanical structures worn on the fingers.

Light-weight solutions include Grabity [9], which emulates multiple aspects of grasp between the thumb and the fingers, and Wolverine [10], which renders sensation of 2D geometric shapes between the fingertips. Since exoskeletons focus on force feedback on the fingers without emulation of cutaneous feedback for the entire hand, the sensation of skin contact with the objects is lost.

Physical Proxy Interfaces

To enable a more natural grasp with rich haptic sensation in VR, real-world props that are similar to the virtual objects have been proposed as physical proxies for hand manipulation [19] and have been shown to enhance realism [20, 7]. Passive proxies can be prepared beforehand for specific tasks [33] or be fabricated per specific shapes and weights [13]. Annexing Reality [18] leverages real world surroundings to search and map appropriate objects nearby to the virtual objects dynamically. Retargeting techniques [2, 8] use visual illusions to reuse passive objects. However, the number and placement of passive proxies depend on the given environment, and they are less responsive to VR content. Though Zhao, et al., [40] demonstrates dynamic self-assembly small robotic blocks to serve as active proxies, the shape-changing process is limited on the table. Last but not least, since these proxies are physical objects, some manipulation such as throwing is not well supported.

Visuo-haptic Illusion

Proxies have been shown to enhance the experiences in VR even if they do not perfectly match the virtual objects [19, 34]. Kwon, et al., [25] studied the effect of mismatched shapes and sizes of props on the performance of object manipulation. They find that mismatched sizes only made grasping time longer but had no significant effect on manipulation time. Simeone, et al., [34] conducted studies to understand which mismatched properties of an object would be more significant to users. They found that mismatch of *function*, *i.e.*, mismatch between the affordances of physical and virtual elements, would break the illusion; other properties such as weight can be largely altered without losing the sense of immersiveness. For objects used for wielding, weight illusion can be leveraged to create the sensation of virtual objects with different length [13, 39] , while a similar mechanism is used in shape-changing mobiles [16, 17]. Inspired by prior works, we aim to provide proxies that support different shapes for various kinds of grasping and manipulation. Specifically, we focus on the grasping part of virtual objects.

Pneumatic Shape-changing Interfaces

Our prototypes are mainly based on pneumatic interfaces for its ability to dynamically change its volume while remaining light-weight. Pneumatic interfaces have been introduced into HCI as shape-changing interfaces [23, 24]. Soft materials that deform and adapt to the virtual contents allow more realistic user interfaces [21]. Harrison, et al., [15] use fabricated pneumatic overlay to provide a dynamic physical user interface on flat screens. PneUI [38] demonstrates several prototypes rendering curvatures, volumes, and textures using pneumatic actuation. AeroMorph [29] uses heat-sealing with a computational fabrication technique to design 2D expandable pneumatic structures that fold into 3D shapes, and Printflatables [31] expands the technique to human-scale fabrication. Based on this knowledge, we develop techniques to leverage pneumatic interfaces as active shape proxies for VR.

DESIGN OBJECTIVES

We have designed PuPoP to serves as a shape-proxy interface for VR, focusing on the following design objectives:

Wearability. The props should be light-weight and wearable to enable always-available physical proxy interface in the VR interactive environment. The props should be able to pop up if needed and fold into a nearly flat surface when not needed.

Shapes for affordances. The shapes should be able to cover common object manipulation in VR. In this work, we focus on shapes of objects for one-handed manipulation.

Interactivity. The props should allow sensing of finger operation such as grasping. To enhance the sense of realism in VR, emulation of certain material properties like stiffness would be preferred.

DESIGN & IMPLEMENTATION

We describe the hardware system, the design of pneumatic folding structures (see Figure 2 for an overview), and the integration with VR in the following subsections.

Pneumatic Control System

The pneumatic control system includes portable air pumps (RS-555PH-19143, DC24V, for the fast pump and Kamoer KVP04, DC12V, for the shape-maintaining pumps), solenoid valves (ZHV-0519, ZonHen), air pressure sensors (MIS-2500-015G, Metrodyne Microsystems), silicone tubes, and T-shape tube adaptors. The power consumption of our prototype is 24 W. The components are controlled through an Arduino micro-controller and communicate through a Serial port with a Unity 3D program that manages the VR content.

Our system allows multiple airbags to be inflated or deflated while maintaining other airbags at a certain high or low level

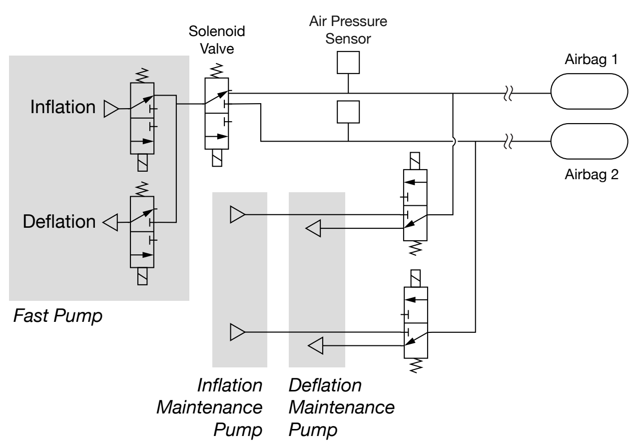

Figure 3. Airbag tubing schematics of the pneumatic control system.

of air pressure. Each of the airbags is connected to three subsystems: the fast pump, the inflation maintenance pump, and the deflation maintenance pump. The switching of the subsystem is achieved through the sensing of air pressure and the controlling of several solenoid valves. The pneumatic system is illustrated in Figure 3.

The fast pump subsystem consists of a large air pump to accelerate the inflation and deflation. Airflow of over 12 L per minute can be achieved. The average inflation and deflation times of small, medium and large airbags by our PuPoP prototype as discussed herein are 0.9, 1.6, 2.6 seconds, respectively. Since the air pump can only inflate in one direction, we incorporate two solenoid valves to switch the airflow.

For the airbag in fully inflated or deflated state, we switch its connection to the maintenance pumps. For maintaining the inflation of the airbags, an air pump with PWM speed control ability is used to compensate for any small air leakage that might happen in the system and maintain the gauge pressure at about 28 kPa, making the airbags remain tautly inflated. For deflation of the airbags, another air pump is used to maintain a vacuum pressure at about 2.3 kPa so the airbags that are not in use will stay flat.

We implemented a system that supports two channels of airbags, though more channels could be realized with more solenoid valves. The tubes and wires connected to the airbags can be detached and attached easily using tube adapters and jump wires before switching VR applications.

Identify Primitive Shapes

We first decided the primitive shapes that can cover common scenarios of object manipulation in VR. Depending on the grasping posture, which changes according to the task requirements, a grasp can be categorized into a *power grasp* (mostly palm opposite) or a *precision grasp* (mostly pad opposite) [27]. According to a more detailed taxonomy of grasp, there are mainly two subdivisions for each category: prismatic (wrap symmetry, cylindrical) grasps and circular (radial symmetry, spherical) grasps. For example, power grasps include throwing a ball (circular type) and wielding a sword (prismatic type); precision grasps includes picking up a small object (circular type) and holding a thin stick (prismatic type). From the aforementioned literature, a sphere and a cylinder should be considered as essential in order to support common object manipulation in the real world.

To discover more primitive shapes, we look into common objects that appear in actual VR games on the market currently. Two of our authors watched game trailers for popular VR games on the mainstream PC game platform Steam. In total, we watched 20 trailers (including sports games, action games, and simulation games) and labeled all the objects that appear being held in hand. All 111 labeled objects were then categorized by approximating objects to primitive shapes. For objects larger than hands, only the shapes in contact with hands were considered. 44 of the objects (rackets, bottles, hammers, and swords, etc.) can be approximated to cylinders. 11 of the objects (balls in sports, snowballs, bombs, and grenades, etc.) can be approximated to spheres. 27 of the objects (sandwiches, books, milk package, and camera, etc.) can be approximated to rectangular boxes. While other objects such as a carrot can be approximated to a cone, a Frisbee can be approximated to a disk, and a bowl can be approximated to a hemisphere, these objects accounted for fewer instances of use. We also found mechanical objects, such as scissors, malleable objects, such as clothes and chains, and animals, such as fish and cats. These objects can not be easily approximated to any primitive shapes. To allow for consistency with the prior research and sufficient variation to cover as many objects as possible, we concluded that spheres, cylinders, and rectangular boxes are the three most critical primitives, while cones, disks, and hemispheres are optional.

Material & Shape Folding Structures

We aimed to design the shape-folding structures with thin and light-weight material for wearability. Latex, as an example of the elastic material used by Harrison, et al., [15] turns out to be well-rounded and soft when inflated. Inspired by Sticky Actuator [28], we utilized non-elastic PE sheets. While thicker sheets are more robust and can withstand much higher air pressure making the props feel more solid, thinner sheets fold into thinner planes. Finally, we choose the 0.08 mm PE sheet due to its durability for repetitive inflation and manipulation. We use a heat-sealer machine (KF-200H) to manually seal the PE sheets one edge at a time after we have cut and folded the sheets.

The Sphere

To create a sphere with a radius r (we denote half of perimeter as $l = \pi r$), we use a sheet with size $l \times 2l$ (see Figure 4). The key to a good sphere is that it should expand evenly in radial directions. We fold the sheet 16 times to allow the structure to be evenly folded and heat-sealed at each end. While a better sphere can be achieved by minimizing the fold width d, this makes the folded material too thick and likely less comfortable to wear.

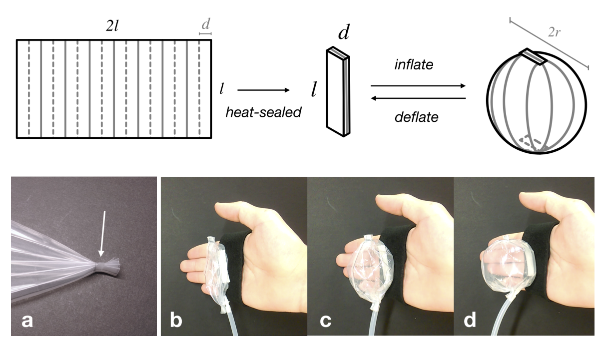

Figure 4. Sphere prop folding structure illustration. a) Each end of the material is heat-sealed after multiple folds. b) Deflated state. c) During inflation. d) Fully inflated.

The Cylinder

To make a cylinder with a radius of r and a height of h , we use two sheets with length $h+2r$ and width l and seal each end together (see Figure 5). We fold each end inward then seal both sides of the cylinder. The additional r at each end allows the airbag to expand at the top and the bottom. We keep the height h at about the size of palm for simulating a long cylindrical object in grasp. Due to the top and the bottom of the cylinder being folded and heat-sealed inward, the cylinder can collapse to become a flat surface.

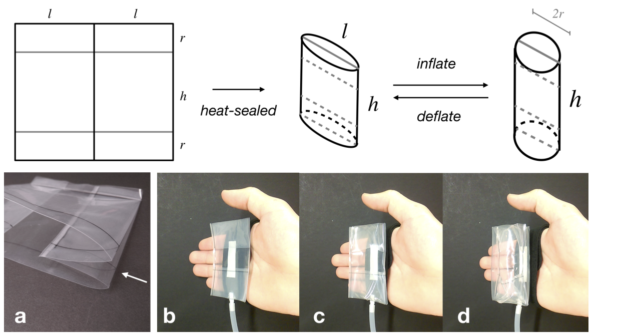

Figure 5. Cylinder prop folding structure illustration. a) Each end of the material is folded inward and heat-sealed. b) Deflated state. c) During inflation. d) Fully inflated.

The Box

To make a box with a width of a and a length of b, we tailor cut material that expands the box from the top side (see Figure 6). The width b, which is folded and collapses inward, must be smaller than a. Since the airbags have a tendency of folding back to its original form as when they were heat-sealed, in order to make the side surface of the box fold inward for minimizing the flattened area, we fold them before heat-sealing. Note that other shapes such as a prism can be realized through a similar folding structure.

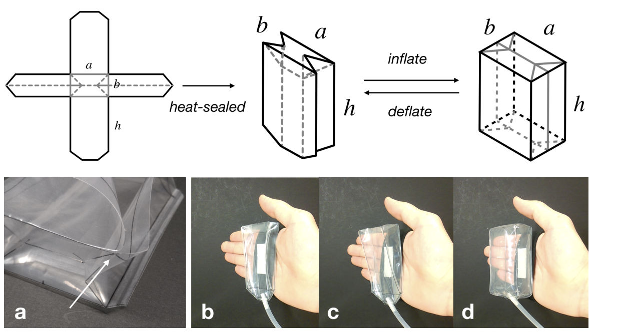

Figure 6. Box prop folding structure illustration. a) Top surface of the material is folded inward before heat-sealed. b) Deflated state. c) During inflation. d) Fully inflated.

Props on Palm

To mount the props on the palm, a fabric strap is wrapped around the palm. The props are affixed to the strap with hook and loop fasteners. In this way, the props can be easily attached to or detached from the palm before switching to different VR applications.

Prop Stacking

To have multiple props on hand for more complicated VR applications, we explore the *prop stacking* technique to mount several airbags onto the palm (see Figure 2 for *prop stacking* illustration). To mount props with different shapes together, two rules are suggested. First, props should have a similar dimension when flattened. Second, props should be stacked in the order of box, cylinder, and sphere, with the box prop being the bottom-most prop on the palm. This allows each shape to pop up while minimizing interference with the others. Props can be stacked in an descending order of size from the palm. In this way, when the smaller airbag is inflated, the larger airbag will not overhang. When the larger airbag is inflated, our deflation system maintains the deflation of the smaller airbag flat on top of the larger airbag without any overhang. Refer to Figure 7 for our implementation of two examples of stacking.

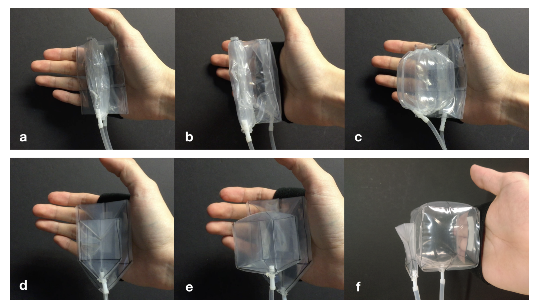

Figure 7. Prop stacking. Shape stacking of a cylinder and a sphere prop: a) Flattened state. b) Cylinder pops up. c) Sphere pops up. Size stacking of two boxes: d) Flattened state. e) Small box pops up. f) Large box pops up.

Prop Extension

All primitive shapes, the sphere, the cylinder, and the box, are designed to be attached right on the palm. This only supports the palm-opposite type of grasp. In order to support the pad-opposite type of grasp such as grasping small objects only with the thumb and the fingers, props need to be lifted off the palm. We developed two kinds of support structures for pushing the prop off the palm and up (see Figure 2 for *prop extension* illustration). One is a *parallel extension*, which is a smaller box airbag, that is attached to the prop to push it into position where it can be grasped by the thumb and fingers. Another kind is a *tilt extension*, which consists of a triangle shape of an airbag to tilt the prop. This allows options such as transforming a normal cylindrical prop into a pen that can be held with the fingers. Refer to Figure 8 for our implementation of two examples of prop extension.

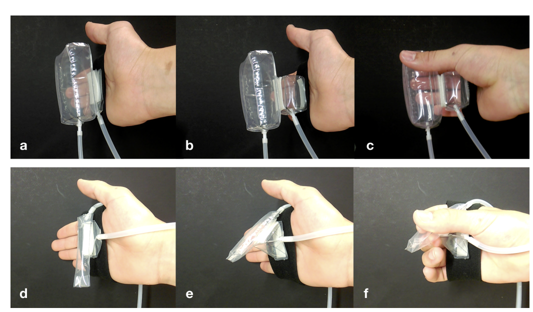

Figure 8. Prop extension. Parallel extension: a) Extension flattened state. b) Extension pops up. c) Holding in precision grasp. Tilt extension: d) Extension flattened state. e) Extension pops up. f) Holding in pen-like tripod grasp.

Prop Sensing

We use Leap Motion for sensing hand position and orientation. When props are not inflated, Leap Motion can track user's fingers; when props are inflated, we use on-prop sensors to detect finger events.

Finger Operation

Though air pressure sensors may be used to detect hand input, we found the air pressure changes caused by slight finger pressing were often indistinguishable from the changes caused by inevitable air leakage. Since our props are made of thin and deformable plastic, flexible force-sensitive sensors (FSRs) can be affixed to the surface of props without affecting the props' haptic sensation. FSRs directly detect the touch events on the object, such as grasping and dropping, and they can also infer how much force is applied to the object by finger manipulation, such as pressing and squeezing. The threshold of the force sensor is measured just once when the prop is inflated and grasped. No further calibration is required.

Object Properties Emulation

Due to the fact that our airbags are actuated by pneumatic pumps, material properties like stiffness and pulsation can be emulated with the same actuation mechanism to enhance the sense of realism in VR. Combining FSRs and pneumatic actuation, emulation of a certain degree of stiffness is possible by controlling the air pump according to the force applied on the object. In this way, we can simulate objects with a range of elasticity. Some pulsing properties of objects, such as heartbeat, can be emulated by designing patterns of sudden inflation to expand and shrink the prop.

Incorporation into VR

We implement the system with the HTC VIVE headset and Leap Motion on the Unity 3D (2017.3) program, which communicates with the pneumatic system. We further developed two types of grasping techniques to incorporate PuPoP into VR:

Natural grasp. We add larger custom colliders in Unity 3D for virtual objects so that we can detect a user's hand when approaching (Figure 9a). In this way, the prop can be inflated in advance (Figure 9b), thus allowing the user to grasp the fully inflated prop in place. As the user grasps the prop, the virtual object will snap to the user's virtual hand and be aligned with the orientation of the prop (Figure 9c). To avoid inflation when the user is not intending to grasp anything, the prop is only inflated when the user's hand is open.

Magic grasp. This kind of grasp is inspired by grasping a Lightsaber in the movie Star Wars, where a Jedi summons his Lightsaber from a distance simply by aiming an open-handed gesture at the object. A user's hand when open casts a ray onto the virtual object in the scene (Figure 9d). If the ray collides with an object for more than one second, the virtual object will fly into the user's hand (Figure 9e, f). In the meantime, the airbag corresponding to the object shape will inflate. The advantage of *magic grasp* is that we can ignore the orientation of the object, that is not possible with the current design of the props.

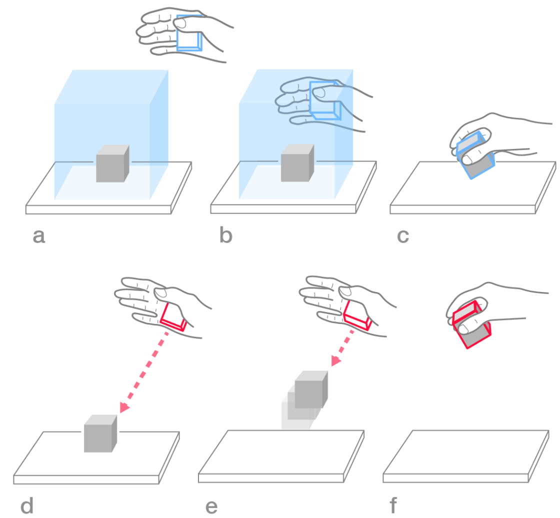

Figure 9. Natural grasp & Magic grasp.

DEMO APPLICATIONS

Two fantasy VR applications with different scenarios of object manipulation have been created to demonstrate the aforementioned designs of PuPoP.

Quidditch Sports Training

We adopt the fictional sports game named Quidditch from the Harry Potter books and create a simplified training game (see Figure 10). This game demonstrates the feasibility for players to throw or catch balls while wearing two spherical props on their palms. Two props have different sizes and are implemented with the *prop stacking* technique. The goal for the players in this game is to get a high score in a limited time. The players have two ways to score: first, they pick up one of the three balls from the red box and throw it into one of the hoop which is suspened from a goal post. Balls in the box are replenished automatically whenever they are depleted. Second, the players can catch the flying Golden Snitch to double their current score. We adopt the *natural grasp* technique for this game, where a prop is inflated or deflated when the players approach or throw away a virtual ball, respectively. The same technique also applies to manipulating the Golden Snitch.

Magic Brush Painting

This is a 3D drawing application demonstrating the shape-changing ability of PuPoP (see Figure 11). A set of cylinder and box props are mounted on the player's palm using the *prop stacking* technique. Their virtual counterparts are a magic brush and a magic eraser, respectively. The box prop is further implemented with the *prop extension* technique to support natural manipulation (pad-opposite grasp) of the eraser. The players use the magic brush to draw freely in the 3D space and use the magic eraser to remove strokes drawn previously. Both cylinder and box props are affixed with FSRs. In this way, strokes are generated or erased only when the grasping force of the cylinder or box prop is higher than a threshold, respectively. The players obtain tools by *magic grasp*, that is, they pick up a tool by aiming at it for one second using their palm on the dominant hand. In the meantime, the corresponding prop is inflated by air pumps.

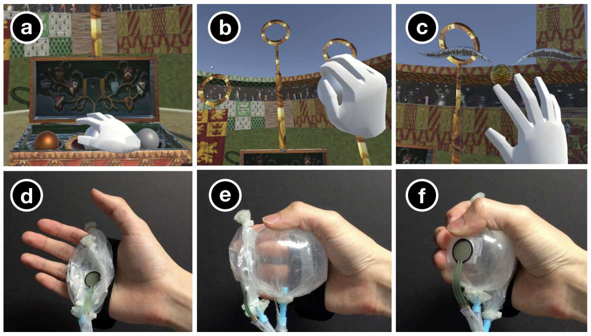

Figure 10. Quidditch Sports Training. a) Pick up a ball. b) Grasp a ball to throw. c) Catch the Golden Snitch. d) Stacked and flattened PuPoP. e) Large sphere for the balls. f) Small sphere for the Golden Snitch.

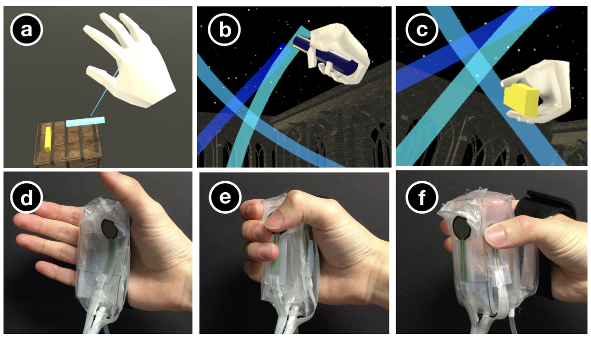

Figure 11. Magic Brush Painting. a) Magic grasp by aiming at the tools. b) Paint with the magic brush. c) Erase with the magic eraser. d) Flattened PuPoP for an empty hand. e) Cylinder prop for the magic brush. f) Extended box prop for the magic eraser.

USER STUDY

We conducted two user studies to understand the applicability of PuPoP. In the first study, we ascertain the visual size acceptance range of the primitive shapes. In the second study, we evaluated the enhancement of enjoyment and realism by comparing PuPoP to other existing interfaces in two demo applications.

Study 1: Visual Size Acceptance Range

According to previous research findings [30, 3, 4], when in conflict, visual sensation often dominates over haptic sensation when a user is perceiving shapes and sizes. The goal of this study is to investigate whether PuPoP could leverage visuo-haptic illusions so that a prop with fixed size could represent multiple virtual objects of similar sizes. We designed this study to understand the visual size acceptance range of each physical prop.

Experimental Design

Nine props (3 primitive shapes, each with 3 sizes) were selected for the experiment. The cube was selected as representative of the box. Let R denotes the side length for cubes and denotes the diameter for spheres and cylinders. The R's for the props are listed in Table 1 along with the study results. We determined the medium size of each shape so that they could be grasped firmly by most people. According to our pilot study, props with a difference in R over about one centimeter would be noticeable in size. As a result, R's for the larger and the smaller props of each shape were determined as one centimeter above and below the R of the medium prop, respectively.

To maintain realism during VR object manipulation, one important consideration is to make sure the visual and haptic stimuli are "coherent" with each other. However, the sensation of coherent visual-haptic feedback could be affected by many factors, such as colors, shapes, and texture of virtual objects. Given the early nature of this research, we focused on only the size of the virtual object itself, with all the other factors excluded, including the hand image in VR. The virtual object was mounted on the virtual palm (though not shown) aligned with the prop mounted on the participants' physical palm, which was tracked by Leap Motion.

The upper and the lower bounds of the visual size acceptance range were found using a one-up-one-down adaptive staircase method [22]. Two staircase runs were conducted for each prop, with one for the upper bound and the other for the lower bound. The initial size of the virtual object was decided with 200% and 10% of R for the upper and the lower bound runs, respectively. The participants were asked to offer their agreements with whether the size of the virtual object in VR matched the size of the prop on their palms. At the beginning of each trial, the size of a step is set to 10% of R. After the first five reversals, the size of a step is set to 5% of R, and after another five reversals, the size of a step is set to 2.5% of R. A staircase run was terminated when there were five reversals of step size equaling to 2.5% of R. The upper or the lower bound was the mean of the sizes of the virtual object at the last five reversals. The order of sizes for each shape was counterbalanced between participants and the order of the upper and the lower bound run was random. In total, there were { 3 shapes $\times$ 3 sizes $\times$ 2 bounds } trials for each participant.

Participants

Twelve paid participants (6 females and 6 males) between the ages of 21 and 26 were recruited for this study. Half of the participants had had experienced with VR on more than five occasions at least, five participants had had experience of VR only twice, and one had never worn a VR headset before. The average hand size and palm width of the participants are 18.0 cm and 8.0 cm, respectively, while all participants are right-handed.

Procedures

Before beginning the study, the participants were invited to sit in a comfortable position and place their left hand on a keyboard. To minimize the visual size distortion in VR, the interpupillary distance (IPD) of the HTC VIVE headset was adjusted to an average distance, 62.5 mm for females and 64.5 mm for males [11]. The researcher first assisted the participants to put on an HTC VIVE headset then mounted the PuPoP apparatus on their right-handed palms using a palm strap, thusly no participants saw the actual props prior to or during this study. The participants were asked to grasp and feel the props freely, and then to offer their responses by pressing the keys on the keyboard with their left hand. The props were mounted on the participants' palms one at a time and were replaced by the researcher when needed. Each trial took about two to five minutes.

Physical Size	Sphere *Small* *48 mm*	Sphere *Medium* *60 mm*	Sphere *Large* *70 mm*	Cylinder *Small* *28 mm*	Cylinder *Medium* *38 mm*	Cylinder *Large* *48 mm*	Box *Small* *40 mm*	Box *Medium* *51 mm*	Box *Large* *64 mm*
Upper Bound	63.2 mm (SE: 2.8 mm) 132%	75.5 mm (SE: 3.0 mm) 126%	95.3 mm (SE: 7.6 mm) 136%	38.0 mm (SE: 2.5 mm) 136%	54.4 mm (SE: 3.5 mm) 143%	70.8 mm (SE: 4.7 mm) 148%	59.2 mm (SE: 3.9 mm) 148%	69.7 mm (SE: 4.0 mm) 138%	88.7 mm (SE: 5.0 mm) 139%
Lower Bound	46.0 mm (SE: 2.2 mm) 96%	60.5 mm (SE: 3.0 mm) 101%	73.4 mm (SE: 3.2 mm) 105%	28.7 mm (SE: 2.2 mm) 102%	42.4 mm (SE: 1.7 mm) 112%	54.1 mm (SE: 3.5 mm) 113%	43.7 mm (SE: 1.9 mm) 109%	53.4 mm (SE: 1.9 mm) 102%	68.2 mm (SE: 2.0 mm) 107%

Table 1. Study 1 Results: Visual size acceptance range of multiple pop-up props.

Results & Discussion

The visual size acceptance ranges of the 9 props are listed in Table 1. Two observations are found from the results of this study. The first is that most of the boundaries are overlapping between the props with different sizes. That is, the upper bounds of smaller props are mostly higher than the lower bounds of the larger props. This indicates that the visual size acceptance range of each prop with different sizes together encompasses a complete spectrum. As a result, without the need to mount many additional props on the palm, PuPoP has the ability to serve as the physical counterpart of virtual objects with sizes over a considerable range. The second observation is that the lower and the upper bounds are on average 3.5% and 36.2% larger than the size of a physical prop. Unexpectedly, most lower bounds are larger than the actual physical sizes of the props. Based on an informal investigation, we found that this may result from the position where we mounted the props. They were not mounted on the center of the palm but mounted a little off the center closer to the fingers. As a result, the participants were slightly constrained to bend their fingers, thus having an illusion that the props were larger than their actual sizes. In this paper, all props are mounted on the same position for comfort and ease of manipulation. The results of this study have provided the first insights into this effect for the design of on-body proxy interfaces. Identifying effective design parameters is an interesting future work.

Study 2: VR Enjoyment & Object Realism

We conducted Study 2 to investigate the extent to which our PuPoP prototypes increase the level of enjoyment and object realism in actual VR experiences. We compared PuPoP with two baseline interfaces: the HTC VIVE controller and the free-hand manipulation tracked by Leap Motion. Each participant experienced the two aforementioned demo applications, *Quidditch Sports Training* and *Magic Brush Painting*, using the three interfaces. (In the following paragraph, we denote the former application as *Quidditch* and the latter as *Painting* for brevity.)

Experimental Design

The gameplay of these applications is described in prior sections of this paper. Here we focus on our considerations for the study.

According to the conclusions of Study 1, PuPoP is able to leverage visuo-haptic illusions such that a single prop can represent a virtual object with a slightly larger or smaller size within a range of acceptance. As a result, in *Quidditch*, four virtual balls (three normal balls for throwing and one Golden Snitch for catching) with different sizes were arranged while only two sphere props served as their actual physical counterparts. We used a small sphere prop to represent virtual balls with 50mm and 60mm in diameter and a large sphere prop to represent virtual balls with 70mm and 80mm in diameter.

To maintain consistency for object manipulation across three interfaces in *Quidditch*, we considered the gesture that matched ball throwing and catching the most closely in the real world. For the HTC VIVE controller, the balls are grasped by holding down the grip buttons on the two sides of the controller, and they are thrown by releasing the grip buttons while wielding the controller. For the free-hand manipulation tracked by Leap Motion, the balls are grasped when a grasping gesture is detected by Leap Motion, and they are thrown when an open-handed gesture is detected while motioning with the hand forward. For PuPoP, the gestures are identical to the free-hand manipulation method, while the only difference is that a prop is inflated or deflated when a ball is grasped or thrown, respectively. To further exclude the effect of differences in performance across the interfaces due to tracking precision, we adjusted the difficulty of the ball throwing so that an average person may achieve a successful throw within five trials using any of the three interfaces.

In *Painting* application, we designed the following methods to maintain consistent manipulation across the three interfaces. For the HTC VIVE controller, the strokes are generated when holding down the grip buttons on the two sides of the controller with a virtual magic brush in hand, and they are erased when performing the same manipulation but with a virtual eraser in hand. For the free-hand manipulation, the strokes are generated or erased when performing a grasping gesture with a virtual magic brush or eraser in hand, respectively. For PuPoP, the strokes are generated or erased when FSRs on the cylinder or the box props received a force over a certain threshold, respectively. To exclude the effect of tracking precision, we downsampled the tracking positions when drawing strokes in the air, thus the drawing results looked similar for all interfaces.

Hand modules are rendered in both *Quidditch* and *Painting* applications. For the free-hand manipulation and PuPoP, tracked hands are rendered using the Leap Motion hand module with an average palm width of 8.5 cm. An identical hand module is employed for controllers but with only two predefined hand postures (an open-handed or a grasping posture) switched by triggering the grip buttons.

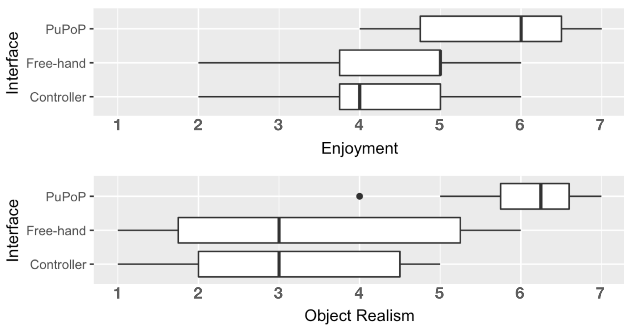

Figure 12. Study 2 results for the *Quidditch* application.

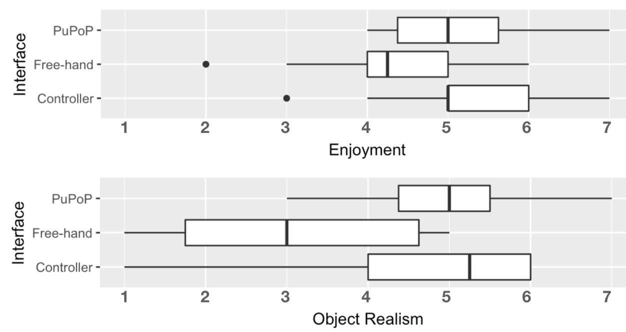

Figure 13. Study 2 results for the *Painting* application.

Participants

Twelve paid participants (6 females and 6 males) between the ages of 21 and 26 took part. Most of the participants had had low experience with VR technologies and two had had none whatsoever. The average hand size and palm width of the participants are 17.5 cm and 8.2 cm, respectively, while two of the participants are left-handed.

Procedures

At the beginning of the study, the participants were instructed to stand in a comfortable position. The researcher then assisted the participants to put on an HTC VIVE headset and a headphone. The experiment consists of three sessions. During each session, the participants experience two applications (*Quidditch* first, then *Painting*) with one of the three interfaces while the order of the interfaces are counter-balanced. Note that for the PuPoP session, the device is placed on the dominant hand of the participants after they had already put on their VR headset; thus no participants saw the PuPoP prior to or during this study. For *Quidditch*, the participants are asked to throw balls into the hoop of a goal post and catch the flying Golden Snitch. We ensured that in this instance all participants performed at least five successful throws. For *Painting*, the participants are asked to draw with a magic brush freely and erase the drawings with an eraser. We ensured that all participants successfully switched tools to draw and erase strokes for at least five times. Each session took about 10 to 15 minutes. At the end of the study, the participants are asked to rate their agreements with statements addressing their experience of *enjoyment* and *object realism* for each interface condition using a continuous 7-point Likert scale. An interview was conducted to collect qualitative feedback.

Results & Discussion

For each application, we conducted repeated-measures one-way ANOVA analysis on both *enjoyment* and *object realism*, in which the independent variables are the three interfaces. The results of these analyses in regard to the *Quidditch* and *Painting* applications are shown in Figure 12 and Figure 13, respectively.

The results of the analysis in regard to *Quidditch* offer two insights. The first is that the participants using PuPoP reported significantly higher *enjoyment* than when using the VIVE controller ($p<0.01$) or the free-hand manipulation method ($p<0.05$). They also reported significantly higher *object realism* when using PuPoP than the VIVE controller ($p<0.0001$) or free-hand manipulation ($p<0.0001$). In post-experience interviews, the participants reported that grasping a ball is realistic when using PuPoP. Though some participants complained about the inflation time that slowed down the interaction for larger balls, most of them found that their enjoyment of the experience was enhanced due to increased realism. Interestingly, most participants are surprised when they caught and actually felt the Golden Snitch when using PuPoP. However, such feedback was not indicated by the statements of the participants when using other interfaces. The second insight is that there is no significant difference found between the controllers and free-hand manipulation in regard to both *enjoyment* and *object realism*. The participants reported that although holding a controller is better than holding nothing, not being able to throw the controller broke the immersiveness of the experience of throwing a ball. Also, some participants reported that the grasping postures are different for use when comparing PuPoP with the VIVE controller. They reported that throwing a ball using a controller feels like wielding a racket, which is considered less realistic. For free-hand manipulation, though the participants grasped nothing physically, they reported being able to grasp and throw the virtual ball with a natural hand posture, making them believe that they were actually throwing a real ball. However, without haptic sensation, the participants often felt confused whether they had successfully grasped or released the balls. Also, they reported that seeing a hand passing through a visual ball broke their sense of realism. In this application, PuPoP provides natural grasping along with approximate physical shape feedback, making the scores of *enjoyment* and *object realism* higher. All participants believe that there are multiple props with different sizes on their palm when using PuPoP, except that one participant realized that there are actually only two props that are used. Others believe that there are at least three props on their palms. This validates the conclusion of Study 1 that PuPoP can leverage visuo-haptic illusion in VR to alter the perceived size of physical props.

We found two observations from the results in regard to *Painting* application. First, PuPoP ($p<0.01$) and the VIVE controller ($p<0.01$) both received significantly higher scores than free-hand manipulation for *object realism*; however, there was no significant difference in regard to perceived object realism when compring PuPoP and the VIVE controller. Based on the post-experience interviews, we believe that there are different reasons for the perceived *object realism* using PuPoP and that perceived using the VIVE controller. PuPoP has the capability of changing from a cylinder-shape brush to a box-shape eraser in this application, a fact that most participants noticed as a difference. However, participants complained that the brush felt too soft to be real, while the controller provided a more rigid feeling that matched their expectation of a real brush. Nonetheless, some participants favored the realism of the eraser due to its perceived softness and grasping posture, while others thought that the controller also had a similar emulation of such grasping posture. For free-hand manipulation, some participants felt that it was awkward to use because, without a physical proxy in their hands, it was unnatural to perform a grasping posture as they would naturally do so when using these tools. As a result, they rated the *object realism* lower for the free-hand method. Second, no significant difference is found between the three interfaces for *enjoyment*. This is because participants had different levels of expectations for painting. Some participants aimed for precise control of strokes with the proxy, while some participants enjoyed free exploration with their bare hands. Last but not least, some participants mentioned that the process of *magic grasp* was congruent with the inflation and the deflation process of PuPoP. In short, both PuPoP and the VIVE controller provided high *object realism* for different reasons. Although *object realism* may be somehow reflected in *enjoyment*, there are no significant differences found in this regard.

In this study, the findings indicate that *object realism* reflects *enjoyment* to some extent. Due to the fact that PuPoP is able to change its shape dynamically in response to different virtual objects across VR applications, it provides overall higher degrees of *object realism* and *enjoyment*.

LIMITATIONS & FUTURE WORK

Grounding. As PuPoP is mounted on the user's palm, it inevitably causes a slight pressure which is not desired for the props with extension. For example, the average normal force applied to the palm when manipulating the pen and the eraser props with extension is 1 N, measured with a force sensor. Interestingly, most participants in Study 2 did not notice the extended airbag, possibly due to the palm strap mitigating the grounding force effect. More user studies are required to understand whether the slight pressure has any effect on immersiveness.

Illusion. In Study 2, it is also found that the participants sometimes grasped the portion of the props which was not designed for grasping, thus degrading the experience of immersion. For example, the participants may grasp the lid of a cylinder prop and felt confused by the haptic feedback they perceived. This raises the question, "To what extent should a prop emulate an object so that realism holds throughout manipulation?" Fujinawa, et al., [13] explore a computational method to fabricate physical props for wielding using the shape and weight illusion. For other grasping manipulation, such as precision grasp, more research is needed in regard to the degree of immersion.

Portability & Inflation time. The current implementation is limited by the inflation time. Due to portability and power consumption considerations, only small air pumps are adopted for our prototype. To make the pneumatic system suitable for practical usage, we may use lithium batteries and change to faster pumps. If portability is not a concern, using a large air compressor along with a vacuum machine could significantly reduce the inflation and deflation time; however, for larger props, the inflation time could still take long. We can compensate for the inflation and deflation time by visual effects to make the visual transformation process coherent with the state of the prop on the palm. For example, growing or glowing effects during the transformation process might be appropriate. Other approaches such as the *magic grasp* technique have been evaluated in Study 2 and received positive feedback.

Stiffness. Another inherent limitation we found in Study 2 is that the stiffness of PuPoP is slightly less than what users might consider rigid. Stiffness could be strengthened using stronger air pumps to maintain high pressure in airbags, though it requires thicker material to withstand the pressure. For a wearable configuration, we choose a light-weight material over any thick ones. Other researchers have experimented with ways to dynamically change the stiffness of an object using a pneumatic jamming technique [12], even in wearable forms [35, 41]. We believe that combining such a technique with PuPoP might be a possible solution to strengthen stiffness.

Complex shapes. PuPoP is presented with primitive shapes in this paper; however, airbags designed with more complex shapes are possible. Researchers have explored fabrication design using pneumatic actuation, such as complex inflatable structures with a computational technique [36]. Others combine elastic and non-elastic materials to provide richer object elasticity [26]. Though complex shape structures are expected, we have demonstrated that props with primitive shapes can largely enhance realism and enjoyment in VR.

CONCLUSIONS

In this paper, we present the concept and prototype of a light-weight wearable Pop-up Prop on Palm (PuPoP) that serves as a 3D shape-proxy interface for VR. Several PuPoP shape structures, along with stacking and extension techniques, have been designed. We conducted user studies to understand the visual size acceptance range of PuPoP and evaluated the interface in comparison with controllers and free-hand manipulation in two VR applications. Our research results suggest that PuPoP enhances enjoyment by increasing object realism. While the current implementation is limited by inflation time and prop stiffness, this problem could be solved by appropriate VR content design. Through our preliminary study, we believe that PuPoP is a simple yet effective way to convey haptic shapes in VR.

ACKNOWLEDGEMENTS

This research was supported in part by the Ministry of Science and Technology of Taiwan (MOST106-2221-E-002-211-MY2, 106-2923-E-002-013-MY3, 107-2218-E-011-016, 107-2636-E-011-003-) and National Taiwan University.

REFERENCES

1. 2018. Cybergrasp, CyberGlove Systems Inc. http://www.cyberglovesystems.com/cybergrasp/. (2018). Accessed: March 19, 2018.
2. Mahdi Azmandian, Mark Hancock, Hrvoje Benko, Eyal Ofek, and Andrew D. Wilson. 2016. Haptic Retargeting: Dynamic Repurposing of Passive Haptics for Enhanced Virtual Reality Experiences. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. ACM, New York, NY, USA, 1968–1979. DOI: http://dx.doi.org/10.1145/2858036.2858226
3. Y. Ban, T. Kajinami, T. Narumi, T. Tanikawa, and M. Hirose. 2012a. Modifying an identified curved surface shape using pseudo-haptic effect. In *2012 IEEE Haptics Symposium (HAPTICS)*. 211–216. DOI: http://dx.doi.org/10.1109/HAPTIC.2012.6183793
4. Yuki Ban, Takuji Narumi, Tomohiro Tanikawa, and Michitaka Hirose. 2012b. Modifying an Identified Position of Edged Shapes Using Pseudo-haptic Effects. In *Proceedings of the 18th ACM Symposium on Virtual Reality Software and Technology (VRST '12)*. ACM, New York, NY, USA, 93–96. DOI: http://dx.doi.org/10.1145/2407336.2407353
5. Hrvoje Benko, Christian Holz, Mike Sinclair, and Eyal Ofek. 2016. NormalTouch and TextureTouch: High-fidelity 3D Haptic Shape Rendering on Handheld Virtual Reality Controllers. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology (UIST '16)*. ACM, New York, NY, USA, 717–728. DOI: http://dx.doi.org/10.1145/2984511.2984526
6. M. Bouzit, G. Burdea, G. Popescu, and R. Boian. 2002. The Rutgers Master II-new design force-feedback glove. *IEEE/ASME Transactions on Mechatronics* 7, 2 (June 2002), 256–263. DOI: http://dx.doi.org/10.1109/TMECH.2002.1011262
7. Brent Edward Insko. 2001. *Passive haptics significantly enhances virtual environments*. Ph.D. Dissertation. http://www.cs.unc.edu/techreports/01-017.pdf
8. Lung-Pan Cheng, Eyal Ofek, Christian Holz, Hrvoje Benko, and Andrew D. Wilson. 2017. Sparse Haptic Proxy: Touch Feedback in Virtual Environments Using a General Passive Prop. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17)*. ACM, New York, NY, USA, 3718–3728. DOI: http://dx.doi.org/10.1145/3025453.3025753
9. Inrak Choi, Heather Culbertson, Mark R. Miller, Alex Olwal, and Sean Follmer. 2017. Grabity: A Wearable Haptic Interface for Simulating Weight and Grasping in Virtual Reality. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology (UIST '17)*. ACM, New York, NY, USA, 119–130. DOI: http://dx.doi.org/10.1145/3126594.3126599
10. Inrak Choi and Sean Follmer. 2016. Wolverine: A Wearable Haptic Interface for Grasping in VR. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology (UIST '16 Adjunct)*. ACM, New York, NY, USA, 117–119. DOI: http://dx.doi.org/10.1145/2984751.2985725
11. Neil A. Dodgson. 2004. Variation and extrema of human interpupillary distance. In *Stereoscopic Displays and Virtual Reality Systems XI*, Vol. 5291. International Society for Optics and Photonics, 36–47. DOI: http://dx.doi.org/10.1117/12.529999
12. 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*. ACM, 519–528.
13. Eisuke Fujinawa, Shigeo Yoshida, Yuki Koyama, Takuji Narumi, Tomohiro Tanikawa, and Michitaka Hirose. 2017. Computational Design of Hand-held VR Controllers Using Haptic Shape Illusion. In *Proceedings of the 23rd ACM Symposium on Virtual Reality Software and Technology (VRST '17)*. ACM, New York, NY, USA, 28:1–28:10. DOI: http://dx.doi.org/10.1145/3139131.3139160
14. James J. Gibson. 1986. The theory of affordances. *The Ecological Approach To Visual Perception* (1986), 127–143.
15. Chris Harrison and Scott E. Hudson. 2009. Providing Dynamically Changeable Physical Buttons on a Visual Display. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '09)*. ACM, New York, NY, USA, 299–308. DOI: http://dx.doi.org/10.1145/1518701.1518749
16. Fabian Hemmert, Susann Hamann, Matthias Löwe, Anne Wohlauf, and Gesche Joost. 2010a. Shape-changing Mobiles: Tapering in One-dimensional Deformational Displays in Mobile Phones. In *Proceedings of the Fourth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '10)*. ACM, New York, NY, USA, 249–252. DOI: http://dx.doi.org/10.1145/1709886.1709936
17. Fabian Hemmert, Susann Hamann, Matthias Löwe, Anne Wohlauf, Josefine Zeipelt, and Gesche Joost. 2010b. Take Me by the Hand: Haptic Compasses in Mobile Devices Through Shape Change and Weight Shift. In *Proceedings of the 6th Nordic Conference on Human-Computer Interaction: Extending Boundaries (NordiCHI '10)*. ACM, New York, NY, USA, 671–674. DOI: http://dx.doi.org/10.1145/1868914.1869001
18. Anuruddha Hettiarachchi and Daniel Wigdor. 2016. Annexing Reality: Enabling Opportunistic Use of Everyday Objects As Tangible Proxies in Augmented Reality. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. ACM, New York, NY, USA, 1957–1967. DOI: http://dx.doi.org/10.1145/2858036.2858134

19. Ken Hinckley, Randy Pausch, John C. Goble, and Neal F. Kassell. 1994. Passive Real-world Interface Props for Neurosurgical Visualization. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '94)*. ACM, New York, NY, USA, 452–458. DOI:http://dx.doi.org/10.1145/191666.191821

20. H. G. Hoffman. 1998. Physically touching virtual objects using tactile augmentation enhances the realism of virtual environments. In *Proceedings. IEEE 1998 Virtual Reality Annual International Symposium (Cat. No.98CB36180)*. 59–63. DOI: http://dx.doi.org/10.1109/VRAIS.1998.658423

21. David Holman and Roel Vertegaal. 2008. Organic User Interfaces: Designing Computers in Any Way, Shape, or Form. *Commun. ACM* 51, 6 (June 2008), 48–55. DOI: http://dx.doi.org/10.1145/1349026.1349037

22. Da-Yuan Huang, Ruizhen Guo, Jun Gong, Jingxian Wang, John Graham, De-Nian Yang, and Xing-Dong Yang. 2017. RetroShape: Leveraging Rear-Surface Shape Displays for 2.5D Interaction on Smartwatches. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology (UIST '17)*. ACM, New York, NY, USA, 539–551. DOI: http://dx.doi.org/10.1145/3126594.3126610

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

24. 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

25. E. Kwon, G. J. Kim, and S. Lee. 2009. Effects of sizes and shapes of props in tangible augmented reality. In *2009 8th IEEE International Symposium on Mixed and Augmented Reality*. 201–202. DOI: http://dx.doi.org/10.1109/ISMAR.2009.5336463

26. Li-Ke Ma, Yizhonc Zhang, Yang Liu, Kun Zhou, and Xin Tong. 2017. Computational Design and Fabrication of Soft Pneumatic Objects with Desired Deformations. *ACM Trans. Graph.* 36, 6 (Nov. 2017), 239:1–239:12. DOI: http://dx.doi.org/10.1145/3130800.3130850

27. C. L. MacKenzie and T. Iberall. 1994. *The Grasping Hand*. Elsevier.

28. Ryuma Niiyama, Xu Sun, Lining Yao, Hiroshi Ishii, Daniela Rus, and Sangbae Kim. 2015. Sticky Actuator: Free-Form Planar Actuators for Animated Objects. In *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '15)*. ACM, New York, NY, USA, 77–84. DOI: http://dx.doi.org/10.1145/2677199.2680600

29. Jifei Ou, Mélina Skouras, Nikolaos Vlavianos, Felix Heibeck, Chin-Yi Cheng, Jannik Peters, and Hiroshi Ishii. 2016. aeroMorph - Heat-sealing Inflatable Shape-change Materials for Interaction Design *(UIST '16)*. ACM Press, 121–132. DOI: http://dx.doi.org/10.1145/2984511.2984520

30. Irvin Rock and Jack Victor. 1964. Vision and Touch: An Experimentally Created Conflict between the Two Senses. *Science* 143, 3606 (Feb. 1964), 594–596. DOI: http://dx.doi.org/10.1126/science.143.3606.594

31. Harpreet Sareen, Udayan Umapathi, Patrick Shin, Yasuaki Kakehi, Jifei Ou, Hiroshi Ishii, and Pattie Maes. 2017. Printflatables: Printing Human-Scale, Functional and Dynamic Inflatable Objects. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17)*. ACM, New York, NY, USA, 3669–3680. DOI: http://dx.doi.org/10.1145/3025453.3025898

32. Samuel B. Schorr and Allison M. Okamura. 2017. Fingertip Tactile Devices for Virtual Object Manipulation and Exploration. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17)*. ACM, New York, NY, USA, 3115–3119. DOI: http://dx.doi.org/10.1145/3025453.3025744

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

34. Adalberto L. Simeone, Eduardo Velloso, and Hans Gellersen. 2015. Substitutional Reality: Using the Physical Environment to Design Virtual Reality Experiences. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*. ACM, New York, NY, USA, 3307–3316. DOI: http://dx.doi.org/10.1145/2702123.2702389

35. Timothy M. Simon, Ross T. Smith, and Bruce H. Thomas. 2014. Wearable Jamming Mitten for Virtual Environment Haptics. In *Proceedings of the 2014 ACM International Symposium on Wearable Computers (ISWC '14)*. ACM, New York, NY, USA, 67–70. DOI: http://dx.doi.org/10.1145/2634317.2634342

36. Mélina Skouras, Bernhard Thomaszewski, Peter Kaufmann, Akash Garg, Bernd Bickel, Eitan Grinspun, and Markus Gross. 2014. Designing Inflatable Structures. *ACM Trans. Graph.* 33, 4 (July 2014), 63:1–63:10. DOI: http://dx.doi.org/10.1145/2601097.2601166

37. S. H. Winter and M. Bouzit. 2007. Use of Magnetorheological Fluid in a Force Feedback Glove. *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 15, 1 (March 2007), 2–8. DOI: http://dx.doi.org/10.1109/TNSRE.2007.891401

38. Lining Yao, Ryuma Niiyama, Jifei Ou, Sean Follmer, Clark Della Silva, and Hiroshi Ishii. 2013. PneUI: pneumatically actuated soft composite materials for shape changing interfaces *(UIST '13)*. ACM Press, 13–22. DOI:http://dx.doi.org/10.1145/2501988.2502037

39. A. Zenner and A. Krüger. 2017. Shifty: A Weight-Shifting Dynamic Passive Haptic Proxy to Enhance Object Perception in Virtual Reality. *IEEE Transactions on Visualization and Computer Graphics* 23, 4 (April 2017), 1285–1294. DOI: http://dx.doi.org/10.1109/TVCG.2017.2656978

40. Yiwei Zhao, Lawrence H. Kim, Ye Wang, Mathieu Le Goc, and Sean Follmer. 2017. Robotic Assembly of Haptic Proxy Objects for Tangible Interaction and Virtual Reality. In *Proceedings of the 2017 ACM International Conference on Interactive Surfaces and Spaces (ISS '17)*. ACM, New York, NY, USA, 82–91. DOI: http://dx.doi.org/10.1145/3132272.3134143

41. Igor Zubrycki and Grzegorz Granosik. 2017. Novel Haptic Device Using Jamming Principle for Providing Kinaesthetic Feedback in Glove-Based Control Interface. *Journal of Intelligent & Robotic Systems* 85, 3-4 (March 2017), 413–429. DOI: http://dx.doi.org/10.1007/s10846-016-0392-6