HaptiCylinder: Shape-Changing Proxy for VR

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Abstract

We present *HaptiCylinder*, a lightweight gear-driven proxy that smoothly expands its graspable diameter from 50 to 80 mm while preserving consistent circular geometry. Unlike conventional adjustable props that rely on discrete parts or heavy linkages, our design achieves continuous and nearly linear expansion through a curved-slot gear and sliding arms. The result is a compact and 3D-printable device ($\leq$500 g) that ensures both stability and user safety. Beyond its mechanical novelty, *HaptiCylinder* supports versatile VR applications: size-adaptive grasp training, multi-tool emulation without prop swaps, illusion enhancement for dynamic growth/shrink content, and psychophysics on visuo–haptic congruency. By combining lightweight construction, robust kinematics, and seamless geometric change, Hapticylinder offers a practical pathway for integrating dynamic object resizing into immersive VR experiences.breaking immersion.

Keywords

Haptics, Virtual Reality, Shape-Changing Proxy, Gear mechanisms, Visuo–haptic congruency, Shape change

1. Introduction

Physical proxies are a simple yet powerful way to deliver haptic cues in VR: users grasp a real object that stands in for a virtual one, gaining immediate benefits in contact geometry, friction, and timing with almost no latency or power budget. [1][2][3][4][5][6] However, most deployed proxies are static in geometry. When a virtual object changes its size, a static proxy either (i) breaks visuo–haptic congruency or (ii)[5] forces cumbersome prop swaps, which undermines immersion and experimental control.

To address this limitation, we introduce *HaptiCylinder*, a shape-changing proxy that can *continuously and linearly* vary its diameter, in contrast to prior devices that only allowed *discrete* size changes. By enabling a single lightweight and reproducible device to represent objects of multiple sizes, HaptiCylinder overcomes the limitations of static proxies while preserving visuo–haptic alignment. This design provides a practical platform for controlled and repeatable studies of grasp adaptation, dynamic object resizing, and tool–handle adjustments, thereby broadening the scope of VR scenarios that can be explored with physical proxies. Moreover, it creates new opportunities for VR-based perception experiments on dynamically resizing virtual objects, including investigations of visuo–haptic congruency, tolerable mismatches, and perceptual thresholds for continuous size change.

2. Related Work

2.1. Active Haptics

A large body of research has explored active haptic systems, in which actuators generate forces or motions for the user. Motor/gear-based gloves and finger exoskeletons have been developed to render grasp blocking or variable resistance for object contact and shape perception (e.g., Dexmo)[7, 8, 9]. High-density vibrotactile arrays encode contact events and 3D directional cues at the fingertips[10, 11], while

APMAR'25: The 17th Asia-Pacific Workshop on Mixed and Augmented Reality, Sep. 26–27, 2025, Busan, South Korea
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mid-air ultrasound focuses energy on the skin for touch-in-air interactions without encumbrance[12]. Soft pneumatic devices modulate pressure or compliance with lightweight bladders, supporting long-wear scenarios and rehabilitation[13]. Smart-material solutions (piezo, SMA) target high-frequency textures or slow shape changes, and can be combined with thermal elements for richer cues[14, 15, 16]. Although these systems provide precise and realistic forces, they often increase mass, power consumption, cost, and integration complexity, which limits their use in room-scale VR.

2.2. Passive Haptics and Visuo–Haptic Illusions

A substantial body of work has examined passive haptics, in which static physical props are aligned with virtual objects to provide tactile realism. Such approaches allow a physical proxy to deliver real geometry and friction at low latency and low cost, and they are frequently augmented by illusion techniques. For example, pseudo-haptics alters visual gain or response mapping to evoke forces or weight without physical actuation[4, 5]. Remapping methods enable a single prop to stand in for many virtual objects[17, 18], and visual size manipulations bias users' judgments of object size or weight[3, 19]. Texture and material cues have also been varied using 3D-printed skins or hair-like structures[20, 21]. Compared to active devices, these strategies are simple and easily deployable, but purely visual remapping continues to struggle with large or time-varying geometric changes.

2.3. Reconfigurable and Deformable Props

To balance expressiveness and simplicity, a growing body of research has explored reconfigurable tangibles and shape displays. Hand-mounted or wearable shape displays modulate local contact geometry around the hand[2, 6], weight-shifting devices alter perceived mass or inertia[1], and deformable tangibles change form under user input or modest actuation[22]. While these approaches are promising, many platforms primarily target desktop use, emphasize local bumps rather than global size changes, or remain too bulky for free-hand VR.

2.4. Gap and Motivation

Despite extensive work on active, passive, and reconfigurable haptics, two key challenges remain for VR scenarios in which the same object changes size over time. First, fixed proxies or purely visual illusions cannot maintain visuo–haptic congruency during continuous growth or shrinkage. Second, active rigs that could address this problem are often too heavy or complex for routine use. These limitations motivate the development of *HaptiCylinder*, a compact and 3D-printable proxy that can physically vary its diameter within a controlled range. Such a design enables realistic transitions, supports perceptual studies on size change, and allows a single proxy to be reused across multiple virtual object sizes without prop swapping.

3. Proposed Device: HaptiCylinder

3.1. Design Goals

The ideal proxy should realistically render changes in object size while remaining lightweight, safe, and practical for VR studies. Based on these considerations, we established the following design goals:

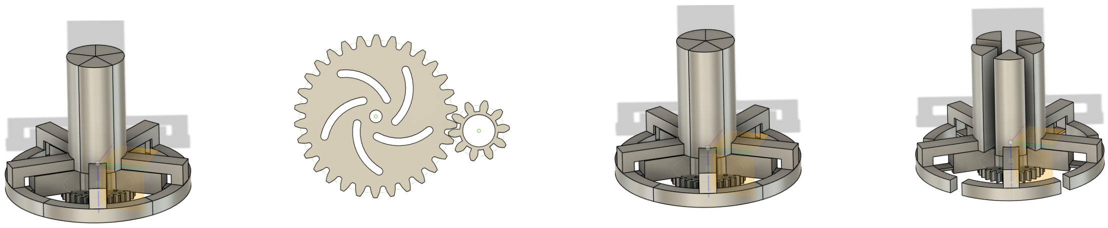
1. The device should allow continuous variation of grasping diameter to support multiple grasp configurations.
2. It must resist typical hand grip forces while remaining compliant enough to backdrive, ensuring interactivity and safety.
3. The device should enable measurement of touch and grip forces applied to the rendered surfaces.
4. Users must encounter the rendered surface without obstruction from embedded actuation components.

5. All actuation and transformation mechanisms should fit within a radius small enough to be comfortably enclosed by the hand.

3.2. Overview

The HaptiCylinder prototype implements these goals in a compact gear–slot mechanism that *continuously* varies its contact diameter from 50 mm to 80 mm (radial stroke 15 mm) while remaining lightweight ($\leq$500 g), 3D–printable, and safe for repeated use. Unlike prior proxies with discrete size changes, it provides smooth, repeatable diameter variation suitable for tasks such as grasp adaptation, growth/shrink scenarios, and tool–handle adjustments without requiring bulky force–feedback hardware.

The assembly consists of a ring frame holding a 30–tooth central gear and a variable–geometry plate with spiral slots that guide five radial sliders. A 10–tooth pinion on the actuator counter–rotates the main gear with a 3:1 reduction. As the plate turns, slider pins follow the spiral slots, extending or retracting the radial bars to linearly change the effective contact diameter (50 mm $\rightarrow$ 80 mm), as illustrated in Figure 1 and Figure 2.



(a) Assembly overview

(b) 10T–30T spur gear pair (3:1)

(c) Before expansion (~50 mm)

(d) After expansion (~80 mm)

Figure 1: Overview of the HaptiCylinder prototype. The device employs a compact gear–slot mechanism to achieve smooth, continuous adjustment of contact diameter (50–80 mm) while remaining lightweight and safe for VR studies.

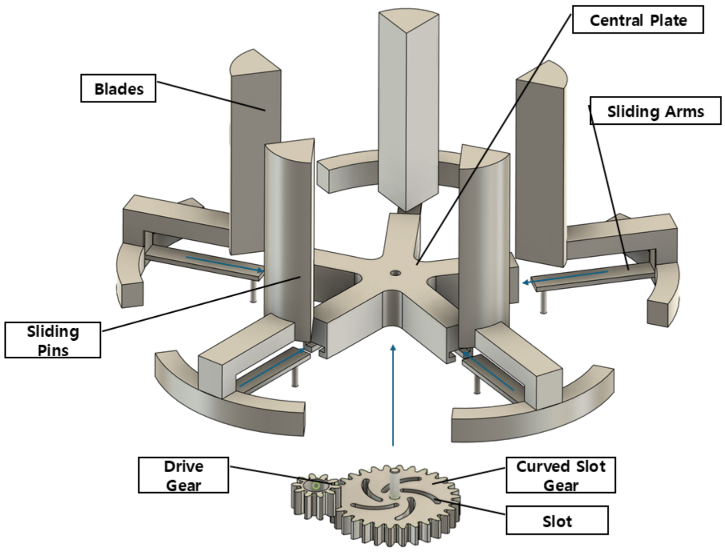


Figure 2: Structural components of the HaptiCylinder. The figure illustrates the blades, sliding arms, and a central plate, which are actuated by a curved-slot plate engaged with a drive gear. Slider pins travel along the curved slots, producing coordinated radial motion that synchronizes the opening and closing of the blades.

3.3. Mechanism Design

To realize a variable–aperture grasping device while preserving circular symmetry, we designed the mechanism to span diameters of $D = 50\text{–}80\,\mathrm{mm}$, covering the most common range of hand–object interactions[1]. This range ensures ergonomic comfort and direct applicability to VR grasp training.

Gear Train and Transmission. The driving stage employs a spur–gear pair with a 10–tooth pinion and a 30–tooth gear, yielding a transmission ratio of

$$i = \frac{z_2}{z_1} = \frac{30}{10} = 3.0,$$

where z_1, z_2 are the respective tooth counts. The cam plate displacement is thus

$$\theta_{\text{slotgear}} = \frac{\theta_{\text{motor}}}{i},$$

with θ_{motor} denoting the motor shaft rotation. This ratio reduces the required motor travel while amplifying output torque:

$$T_{\text{slotgear}} = i \cdot \eta\, T_{\text{motor}},$$

where $\eta \approx 0.9$ is the gear efficiency.

Slot–Slider Actuation. Each blade is guided by a pin–in–slot constraint, with slot geometry following an Archimedean spiral:

$$r(\theta_{\text{blade}}) = a + b\theta_{\text{slotgear}}.$$

To expand the aperture from 50 to 80 mm, the required stroke is $\Delta r = 15\,\mathrm{mm}$. With $b = 0.25\,\mathrm{mm/deg}$, this corresponds to a cam plate rotation of $\Delta\theta_{\text{slotgear}} \approx 60^\circ$, or a motor shaft rotation of $\Delta\theta_{\text{motor}} \approx 180^\circ$, which lies well within the encoder's measurable range.

Torque Requirement. The dominant load arises from the sliders' weight. For $m \leq 0.5\,\mathrm{kg}$ at a lever arm of $r = 40\,\mathrm{mm}$, the required torque is

$$T_{\text{req}} \approx mgr = 0.5 \times 9.81 \times 0.04 \approx 0.20\,\mathrm{N\,m}.$$

The SE–DM185 geared motor provides $T_m \geq 0.08\,\mathrm{N\,m}$ at the shaft. After reduction and efficiency,

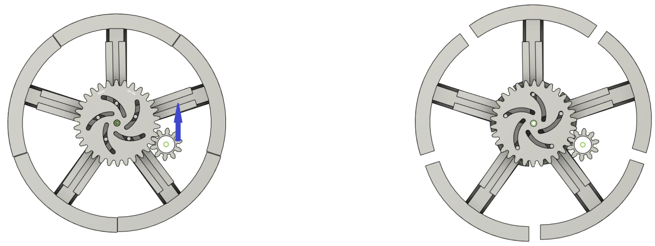
$$T_{\text{slotgear}} \approx 3.0 \times 0.9 \times 0.08 \approx 0.216\,\mathrm{N\,m},$$

which slightly exceeds the requirement, ensuring reliable actuation. The integrated encoder further supports closed–loop feedback near the limits of travel.

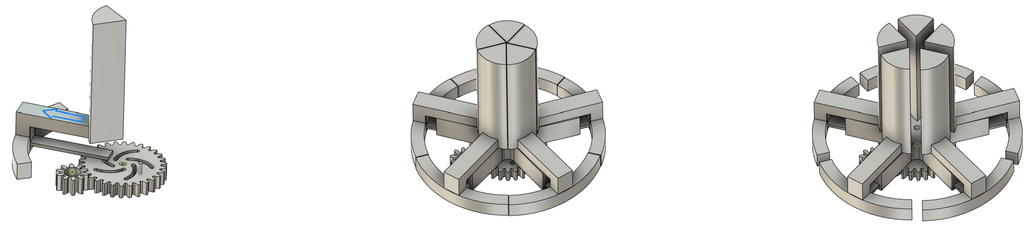
Fabrication and Integration. Structural parts are 3D–printed (PLA+, 0.2 mm layer height, ≥ 3 perimeters). Contact surfaces are polished to minimize friction, and hard end–stops are embedded to protect against overload. The compact assembly integrates easily with VR haptic setups. By balancing slot geometry, gear ratio, and torque margin, the design achieves reliable aperture expansion (50–80 mm) while maintaining ergonomic usability and robustness for VR interaction.

3.4. Operation Pipeline

We summarize the end-to-end chain from a motor command to a change of contact diameter. Let the pinion (10T) angular position be θ_{pinion} and the main gear (30T) be θ_{slotgear}. With the 3:1 transmission, $\theta_{\text{slotgear}} = \theta_{\text{pinion}}/3$. The plate–slot map provides the radius $r(\theta_{\text{slotgear}})$ and the contact diameter is $D = 2r$ (50–80 mm in our prototype).



(a) Top view: before actuation (b) Top view: after actuation



(c) Slot pushes slider (d) Side view: before (e) Side view: after

Figure 3: Pipeline of the Shape-Changing Proxy: a motor drives the pinion, the gear pair rotates the central plate, spiral slots translate rotation into radial motion, and sliders expand/contract the cylindrical contact area.

1. **Motor command.** The controller issues a position/velocity command for the pinion motor (e.g., PWM 500–2500 μs), producing $\dot{\theta}_{\text{pinion}}$.
2. **Pinion $\rightarrow$ main gear.** The 10T pinion drives the 30T gear (3:1), so the plate rotates at $\dot{\theta}_{\text{slotgear}} = \dot{\theta}_{\text{pinion}}/3$.
3. **Plate $\rightarrow$ sliders (slot guidance).** Spiral slots constrain the slider pins; a plate rotation $\Delta\theta_c$ produces a radial change $\Delta r \approx (dr/d\theta_{\text{slotgear}})\,\Delta\theta_{\text{slotgear}}$.
4. **Sliders $\rightarrow$ contact.** Sliders push the arcuate bars outward/inward; the effective cylinder diameter updates as $D = 2r$ (here, $50 \rightarrow 80$ mm).
5. **VR congruency.** The VR application renders the same diameter D (optionally with a small visual gain) to preserve visuo–haptic congruency.

Figure 3 demonstrates the overall actuation mechanism, and Table 1 summarizes the technical specifications.

Table 1

Technical specifications of the HaptiCylinder prototype.

Item	Value / Note
Overall dimensions	∅160 mm × 130 mm (diameter × height)
Total weight	∼350 g (including tracker mount)
Blade assembly	5 blades forming a circular aperture, blade length ∼100 mm
Slider travel	∼30 mm radial sliding per blade
Gear train	10T (1 cm dia) driving 30T (6 cm dia), reduction 3:1
Max opening range	Aperture diameter 50 mm → 80 mm
Frame	3D-printed (PETG/PLA+), structural ribs for stiffness
Power	12 V DC supply, PWM-controlled motor driver
Control	Position/torque via microcontroller (PID loop, 1 kHz)
Safety features	Rounded edges, travel end-stops, blade overlap limits

3.5. Functionality

The device reliably modulates its contact diameter from 50 mm to 80 mm within 200 ms, ensuring that haptic changes remain synchronized with VR visuals. This speed, faster than the typical human reaction time (250–300 ms)[6] allows seamless visuo–haptic congruency during dynamic interactions.

At maximum extension ($r \approx 40$ mm), the torque requirement is about 0.20 N·m, which is marginally exceeded by the geared SE–DM185 motor. Thus, the mechanism can withstand typical grasping forces without stalling.

The integrated encoder provides position and current feedback, enabling force estimation and event triggering (e.g., object breakage or deformation). For safety, the system incorporates three layers of protection: (i) automatic homing at startup, (ii) overcurrent shutdown above 0.5 A, and (iii) compliance of the gear–slot linkage to absorb excessive loads. These features ensure robust and repeatable operation in VR scenarios.

3.6. Final 3D-Printed HaptiCylinder

In the final design iteration, several hardware modifications were implemented to improve usability and safety. First, we combined an identical mechanism in the opposite direction at the top of the device to extend the handle length. This allows users with different hand sizes to securely grip the proxy without discomfort. Second, the structure was redesigned into a closed form, which significantly reduced unwanted wobbling when users held the blade tips during expansion and contraction. This change ensured greater structural stability under repeated actuation cycles. Third, we added a snap band to cover the handle region. This addition provides two key benefits: (i) a smooth tactile surface that improves grip comfort and (ii) effective prevention of finger entrapment that might otherwise occur when the blades contract. Finally, the complete proxy shown in Figure 4 is fully 3D-printable with a simplified assembly process, enabling rapid and low-cost prototyping.

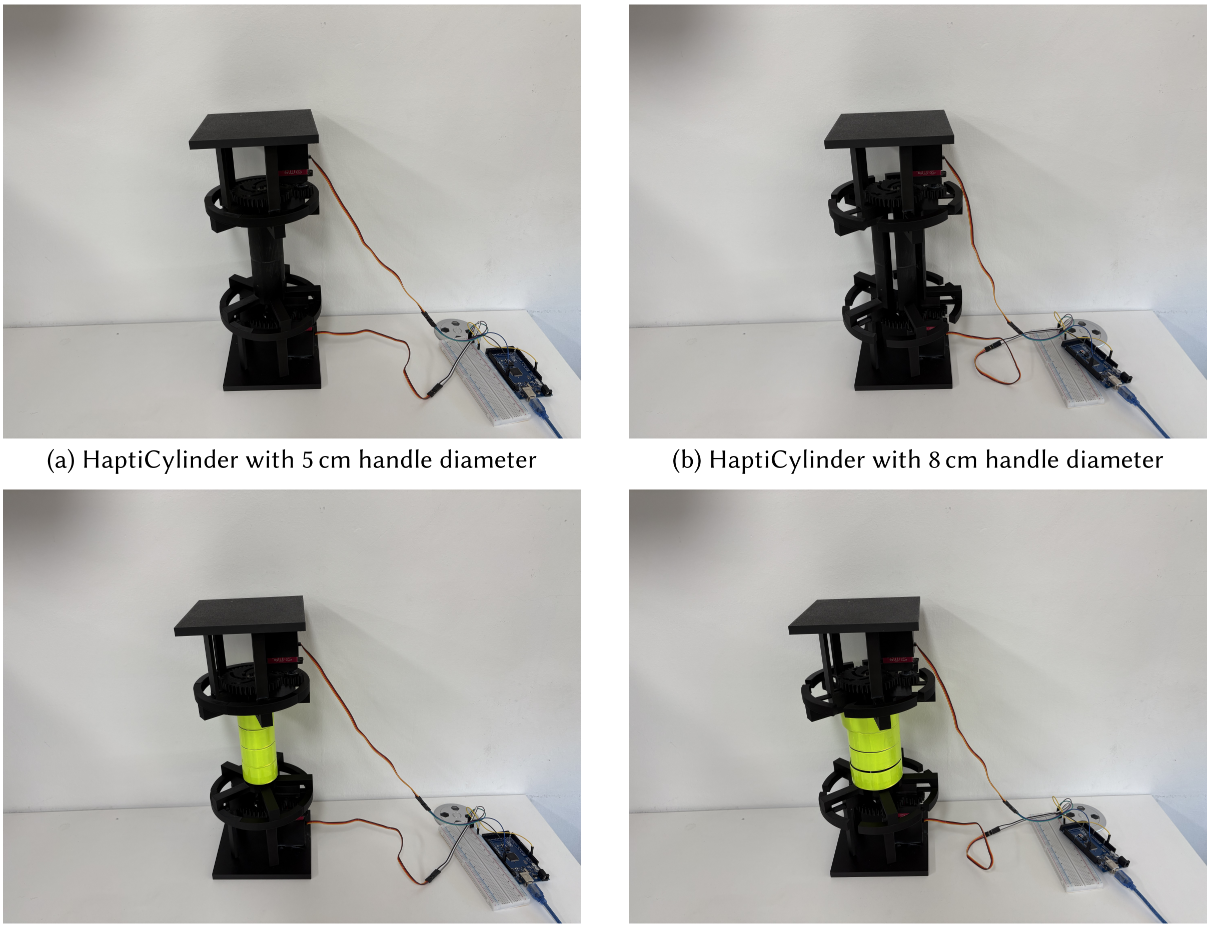
3.7. Applications and Use-Case Scenarios

This work is currently at a work-in-progress stage. We have designed and fabricated the proposed device, and are in the process of developing VR applications and perception studies around it. Since user studies have not yet been conducted, we instead outline several envisioned use-case scenarios where the device can be applied. These examples illustrate the potential range of applications and provide a foundation for future experimental validation. Figure 5 demonstrates example illustrations of the four application scenarios that will be described in the following section.

Size-adaptive grasp training (rehabilitation). The gear–slot mechanism allows the proxy diameter to expand from 50 mm to 80 mm within 200 ms, closely synchronized with visual rendering in VR. This enables patients to perform graded grasp training in which their hand opening is gradually widened while receiving concurrent haptic feedback. As a result, rehabilitation protocols can provide more natural sensorimotor engagement, improving training adherence and recovery outcomes[23].

Force-sensitive object manipulation. The integrated encoder and motor current sensing allow the system to estimate user-applied grip force in real time. When the applied force surpasses a programmable threshold, VR events such as object breaking, deformation, or resistance feedback are triggered. This functionality supports fine-grained force control training, encourages careful motor execution, and enhances realism in tasks that demand delicate manipulation.

Inflatable object immersion. Instead of abstract resistance effects, the device can emulate the physical sensation of an expanding object—similar to a balloon inflating or a crumpled plastic bottle filling with water and regaining its shape. The proxy's fast aperture modulation synchronizes with the



(a) HaptiCylinder with 5 cm handle diameter

(b) HaptiCylinder with 8 cm handle diameter

(c) 5 cm handle with snap band

(d) 8 cm handle with snap band

Figure 4: Final 3D-printed HaptiCylinder prototypes: (a) 5 cm handle hardware, (b) 8 cm handle hardware, (c) 5 cm handle with snap band, and (d) 8 cm handle with snap band.

visual expansion in VR, so users feel the object pressing outward against their grip. This natural visuo-haptic coupling provides a more intuitive metaphor for growth and resistance, enhancing immersion and enabling novel interactive experiences[24].

Versatile virtual object representation. By varying only its aperture size, a single proxy can emulate grips of diverse virtual objects, ranging from small water bottles to larger sports equipment handles (e.g., baseball bats). This versatility reduces the need for multiple haptic devices, simplifies VR setups, and ensures consistent tactile realism across applications such as training, sports simulation, or daily activity rehearsal[25].

(a) Size-adaptive rehabilitation

(b) Force-sensitive manipulation

(c) Inflatable object immersion

(d) Versatile object representation

Figure 5: Illustrative applications and envisioned use-case scenarios of the proposed device.

4. Limitations and Future Work

This work remains at a work-in-progress stage, and its most significant limitation is the absence of user study data to validate the proposed device and envisioned applications. While the current prototype demonstrates technical feasibility, empirical evaluation is essential to substantiate its perceptual effectiveness and practical utility.

Beyond this, the present design primarily affords a cylindrical contact with a single dominant degree of freedom—its aperture diameter. Such a configuration is well-suited for simulating uniform grasping but cannot directly represent non-circular contours, spatially varying compliance, or sharp local features, and its gear-driven actuation may introduce noise or backlash during reversals.

Moving forward, meaningful advances lie in hardware extensions and material innovation. One direction is to generalize the proxy's geometry beyond cylinders, for instance adapting mechanisms similar to XRing[6] to render rectangular, elliptical, or more complex cross-sections, thereby approximating a broader class of virtual objects. Material design also presents opportunities: by embedding 3D-printed microstructures such as hair-like lattices[20] or metareality textures [21], surface roughness and compliance could be encoded into the proxy, extending its expressivity beyond geometry.

Finally, future iterations may integrate sensing and actuation, enabling the device not only to passively respond to grasping but also to autonomously reconfigure in space, supported by modular control architectures that reduce backlash and improve responsiveness. In parallel, small-scale pilot studies should examine perceptual mismatches that may arise when the proxy remains cylindrical while virtual objects undergo dynamic shape transformations. While prior work such as Feick et al. [17] explored grip style and weight perception, the impact of large size or shape changes has yet to be systematically studied. Addressing these scenarios would provide valuable empirical evidence to complement our technical contributions.

Together, these directions provide a path toward expanding the realism, versatility, and empirical grounding of the Hapticylinder.

5. Conclusion

We presented a shape-changing proxy that physically alters its contact geometry to convey virtual object size and form. The device employs a gear-driven mechanism with spiral slots to expand and contract a cylindrical surface, enabling real-time coupling between virtual commands and haptic feedback. Preliminary observations suggest that even with a single dominant degree of freedom, the proxy can elicit convincing perceptual illusions of object resizing and enhance immersion in VR interaction tasks.

Although the current prototype is restricted to cylindrical grasps, the underlying architecture suggests a scalable pathway toward more expressive haptic devices. By rethinking both geometry and material properties, such proxies could evolve into versatile physical surrogates capable of rendering not only size changes but also diverse shapes, textures, and compliance. In the longer term, integrating autonomous actuation and sensing may bridge passive proxies with active agents, enabling embodied, context-aware interaction with virtual environments.

In summary, this work demonstrates the feasibility of mechanically shape-shifting proxies for VR and highlights their potential as a unifying hardware platform for multimodal haptic rendering. As a next step, we plan to conduct a perception study on dynamically reconfigurable proxies—building on the resized grasping paradigm [3]—to investigate how users perceive and adapt to continuous shape changes during interaction.

Acknowledgments

This work was supported by the Institute of Information & communications Technology Planning & Evaluation (IITP) under the Artificial Intelligence Convergence Innovation Human Resources Development (IITP-2025-RS-2023-00254177) grant funded by the Korea government(MSIT)

Declaration on Generative AI

During the preparation of this work, the author(s) used GPT-5 in order to: Grammar and spelling check. Further, the author(s) used GPT-5 for Figure 5 in order to: Generate images. After using these tool(s)/service(s), the author(s) reviewed and edited the content as needed and take(s) full responsibility for the publication's content.

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