The Snail: A Wearable Actuated Prop to Simulate Grasp of Rigid and Soft Objects in Virtual Reality

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Abstract—**The Snail is a wearable haptic interface that enables users to experience force feedback when grasping objects in Virtual Reality. It consists of a 3D-printed prop attached to the tip of the thumb that can rotate thanks to a small actuator. The prop is shaped like a snail to display different grasping sizes, ranging from 1.5 cm to 7 cm, according to its orientation. The prop displays the force feedback, so forces over 100 N can be displayed between fingers using small and low-power actuation. Very rigid objects can be rendered when the prop remains static, but rotations when the users grasp the prop also allow for the simulation of soft objects. The Snail is portable, low-cost, and easy to reproduce because it is made of 3D-printed parts. The design and performance of the device were evaluated through technical evaluations and 3 user experiments. They show that participants can discriminate different grasping sizes and levels of softness with the interface. The Snail also enhances user experience and performances in Virtual Reality compared to standard vibration feedback.**

Index Terms—**Wearable interface, haptic grasp, force feedback, softness, virtual reality.**

I. Introduction

When grasping objects in Virtual Reality (VR), users should feel forces to manipulate these objects correctly and to be immersed in the environment. Objects can be made of rigid (e.g., wood, metal, glass) or soft (e.g., foam, biological samples, fabric) materials, and haptic interfaces are meant to render corresponding force feedback [1]. But their design faces many challenges: they should be able to stop fingers that can exert high forces when grasping objects [2], and they should be portable to be used with VR headsets in large workspaces [3]. They should also be low-cost to remain accessible [2], [4].

Different approaches have been investigated to address these challenges. Among them, exoskeletons surrounding the users' hands can efficiently render grasping feedback on all fingers [5], but they are complex systems that often suffer from bulkiness. Simpler haptic interfaces worn in the inside hand or held, and generating forces thanks to direct actuators [6], [7], brake systems [4], [8] or a combination of both [2] have also been investigated. However, a direct actuation require heavy and power-hungry actuator to counteract the grasping forces, impairing the portability and the cost of the interfaces. Brake systems allow for lighter interfaces but impair the force transmission (e.g., lag, friction [4]) and are not meant to simulate soft objects.

An alternative approach uses passive tangible objects, also called props, to represent virtual objects [9]. Props have the interesting property of rendering convincing rigid force feedback without actuation and can be easily replicated with 3D printing. However, multiple props are generally necessary to represent different virtual objects, and props have fixed shapes, so they can only represent similar or approaching virtual objects in the user's hand [10]. They are also generally rigid, thus they cannot represent soft virtual objects. In the following, we propose an approach to simulate rigid and soft virtual objects of different sizes using only one prop.

This paper introduces the Snail, an interface at the frontiers between actuated interfaces and props. The Snail is made of a prop of a "snail" shape rotating around the thumb fingertip thanks to a direct actuator (Fig. 1(a)). When users grasp virtual objects, the prop rotates to display grasping size (from 1.5 cm to 7 cm) corresponding to virtual objects and simulates force feedback when the index encounters the surface (Fig. 1(b)). Rigid objects can then be simulated. Soft objects can also be rendered by rotating the prop and changing grasping sizes when the users squeeze (Fig. 1(c)). Compared to existing solutions, the grasping forces are simulated by the prop and are tangential to the actuation forces. The Snail can then simulate convincing rigid objects with a small, low-power actuator, making the interface portable. Direct actuation also allows for the simulation of soft objects. Finally, the Snail is mainly made of 3D-printed parts, so it is low-cost and easy to replicate.

The paper makes the 3 following contributions :

- The introduction of the actuated prop approach around the fingertip to display grasping force feedback.
- The design of an interface based on this approach and the implementation of 2 types of interactions: with rigid objects and with soft objects.
- The validation of the interface through technical evaluations and 3 user experiments concerning the interface's effectiveness in simulating rigid and soft objects and concerning its usability in VR environments.

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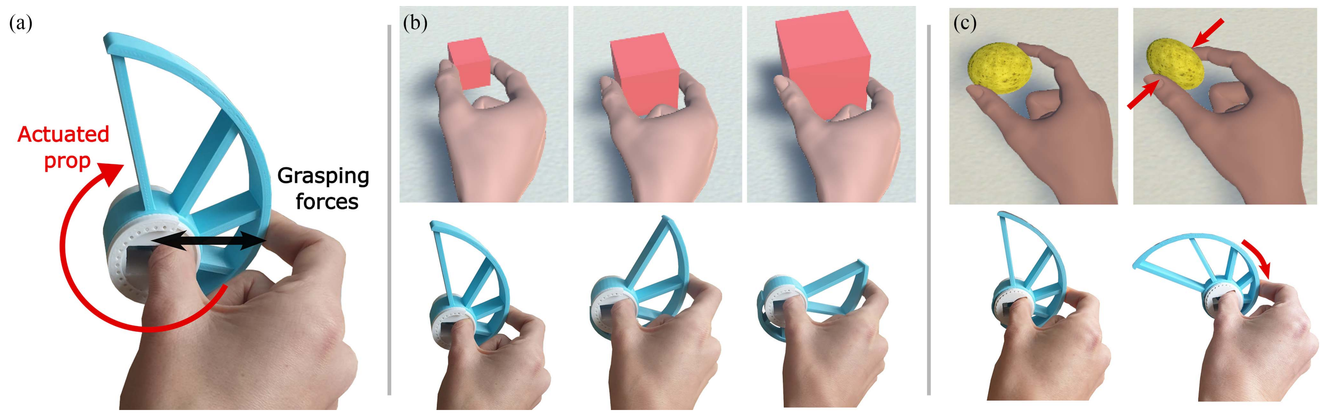

Fig. 1. The Snail uses a prop on the thumb fingertip to provide realistic rigid force feedback when grasping virtual objects (a). An actuator rotates the prop to simulate different grasping sizes before the index finger encounters it (b). Soft virtual objects can also be simulated by rotating the prop when squeezed (c). The Snail uses a low-power actuator as the grasping forces are tangential to the actuation forces. The interface made of 3D-printed parts is also low-cost and easy to replicate.

II. Related Work

This section reviews existing approaches to rendering rigid and soft grasping feedback with haptic interfaces in Virtual Reality. Our work builds on two main concepts: actuated interfaces and prop-based interfaces, which we both discuss specifically.

A. Simulation of Rigid Virtual Objects

1) Actuated Interfaces: Actuated interfaces utilize actuators to provide haptic grasping feedback. Grounded interfaces integrate large actuators to provide convincing force feedback but are fixed in the environment [11], [12], [13]. They have been augmented with encounter-type interactions (e.g., [14], [15]), breaking contact when no force feedback is simulated. However, haptic feedback is still confined to a small area.

In order to increase the workspace, various interfaces carried or worn by users have been proposed. These include tactile interfaces applying pressure or vibrations on the skin [3], [16] or exoskeletons [5] but the former are not meant to stop finger motions, so they cannot display realistic force feedback, while the latter are often bulky.

Haptic feedback that simulates the sensation of grasping a virtual object can be displayed by interfaces held in the user's hands, such as VR controllers [6], [16]. They can integrate heavy actuators, such as the Claw [6], or complex mechanisms, such as the Torc [16], to provide convincing force feedback. Some interfaces also dynamically change their shape to display different objects grasped [17], [18], [19]. All these concepts are difficult to implement on small wearable interfaces on fingers. When using a direct mechanism, the weight and power consumption of the actuators impair the interface's portability. Shape-changing interfaces are more related to interactions on the user's palm, displaying power grasp feedback rather than precision grasp with the fingers [20].

The Gripper and FingerX are wearable interfaces that can provide force feedback through direct actuation [7], [21]. The Gripper has a scissor-like mechanism attached to the fingertips on one side and is actuated by a motor located at the base of the fingers, which directly counteracts the user's forces [7]. FingerX extends a scissors-like mechanism from the thumb to display a platform for the users to interact with the index finger [21]. Small actuators guarantee the interfaces' portability but can only display small force feedback. For instance, only 2.7 N can be displayed continuously by the Gripper, which is significantly lower than the force feedback capabilities of hand-held interfaces (up to 20 N).

Brake-based mechanisms can be used to address this issue [4], [8]. For instance, with Wolverine users slide along a rod when grasping virtual objects, and brake systems stop the movements to simulate force feedback [4]. It can simulate highly rigid feedback (up to 106 N) with a lightweight interface. But simulating soft feedback with brake-based mechanisms is challenging. This paper proposes an alternative solution that combines actuated interfaces with prop-based interfaces.

2) Prop-Based Interfaces: Props are physical objects that represent virtual objects and can provide convincing force feedback [22]. Although some methods have been proposed to create different props easily [23], they are limited to representing only one type of virtual object at one location.

To address the location issue, researchers proposed to use redirection techniques [24], [25]. One prop can then be used to simulate several similar virtual objects at different locations but only in a limited area around the prop. Props have also been combined with actuators to extend their working space [26], [27]. For instance, Wetavix and Pivot are wearable interfaces attached to the users' wrists and positioning a prop in their hands when they grab an object [26], [27].

Still, these interfaces cannot simulate different types of virtual objects. Props have been combined with actuation to change their weights [28]. To simulate different shapes, researchers proposed to use a single prop to simulate different virtual objects and show that if the virtual shapes are approaching the real shapes, such an approach is effective [10], [29]. For instance, when grasping a cube, a set of 3 passive cubes is sufficient to display various haptic feedback corresponding to virtual cubes between 3 cm and 9 cm [29]. The solution remains limited since the prop and virtual objects should have approaching shapes.

An alternative solution is to use a robotic arm to present various props to the users, depending on the virtual objects they are grasping [15]. However, the workspace is restricted, and the system is bulky. Another approach to present different shapes to the users is using swarm robots that assemble to build a haptic prop [30]. This method is complex and time-consuming, making it unsuitable for real-time interactions.

Our proposal builds upon previous works that proposed actuating a prop. However, we use the actuation to display different grasping sizes to the users.

B. Simulation of Soft Virtual Objects

While props appear suitable for rendering rigid feedback, additional investigation is required to properly simulate softness using these systems. This can be performed by exploiting the visual dominance over the haptic when experiencing softness. Users can perceive a passive spring as stiffer or softer if corresponding visual deformation is displayed [31], [32]. Such visual-haptic illusions have been used to simulate soft objects grasping with passive rigid props [33]. However, the approach remains limited to the shift of visual dominance and does not work in some circumstances, for instance, if users do not look at the object being grasped.

An alternative method involves combining a prop interface with tactile feedback. Vibrations can enhance the perceived stiffness or softness of passive objects [34], [35]. The softness can also be adjusted by manipulating skin deformation on the fingertip [36], [37], [38]. It can be modified by limiting fingerpad deformations [38] or stretching the skin upon contact [37]. These techniques require using an additional haptic device on the user's fingertip to simulate the sensation of softness and they do not accurately replicate the finger penetration while grasping soft objects.

To our knowledge, actuating the prop itself to render softness feedback has not been investigated yet. In contrast with existing approaches, it would benefit to simulate the actual penetration of the finger during grasping.

III. Design of the Snail

The Snail is a wearable interface designed to simulate rigid and soft grasping feedback in VR. Our approach consisted of designing a prop that can display different grasping sizes thanks to an actuator. The interface is worn on the thumb fingertip, and when users grasp a virtual object, the prop rotates to display the right grasping size before the index finger encounters the surface.

A. Shape of the Prop

We designed a prop in the shape of a logarithmic spiral. Such spirals have distances between the turns that increase in geometric progression, allowing for the continuous presentation of different grasping sizes while limiting the overall size and weight of the interface. The cartesian coordinates of this spiral can be expressed as:

$$x = ab^{\theta}\cos(\theta) \quad \text{and} \quad y = ab^{\theta}\sin(\theta) \tag{1}$$

with θ the radial angle, and a and b two constants. We chose $a = 0.027$ and $b = 1.425$ for the grasping size to be equal at 1.5 cm for $\theta = 0°$and 7 cm for $\theta = 180°$ (Fig. 3). The maximal angle was chosen to guarantee that the prop will not collide with the hand and to use a small servomotor generally limited to $\theta = 180°$. The structure was designed to limit the weight while resisting high forces in the normal direction. As a result, the prop resembles a snail (Fig. 2).

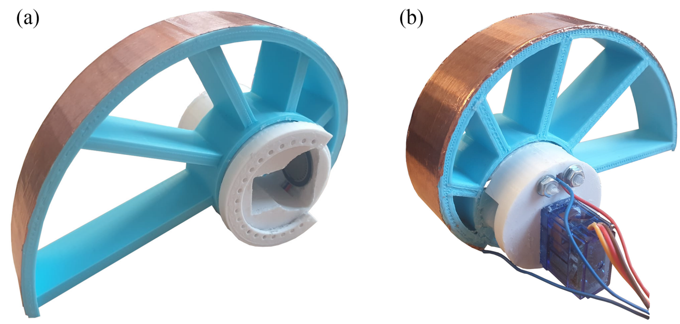

Fig. 2. Close views of the Snail prototype from the front (a) and from the back (b) showing the actuator.

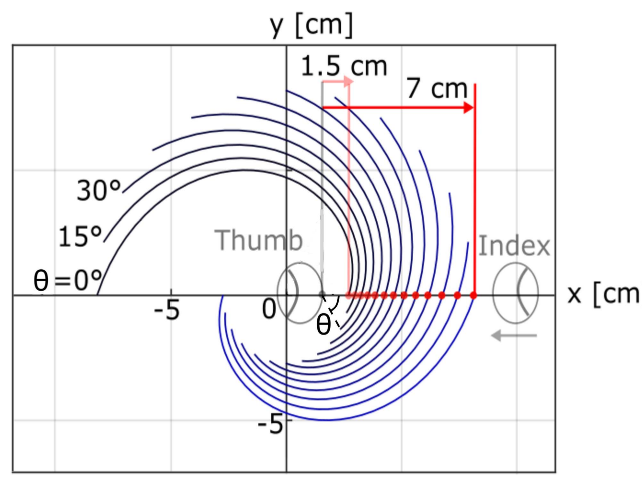

Fig. 3. Representations of the logarithmic spiral for different rotations θ around the thumb. Distance between thumb fingerpad and spiral corresponds to 1.5 cm at $\theta = 0°$ and 7 cm at $\theta = 180°$.

Props do not need to have the same shape as virtual objects to simulate convincing force feedback [10], [29], so we hypothesized that the snail shape could be used to represent round and squared virtual objects as well. This hypothesis was supported by user evaluations presented in Section V-C.

B. Complete Structure and Actuation

The complete structure of the Snail interface is displayed in Fig. 4. The prop (3) rotates around a prop support (4) thanks to a small actuator (1). The rotor is fixed on the prop, and the stator

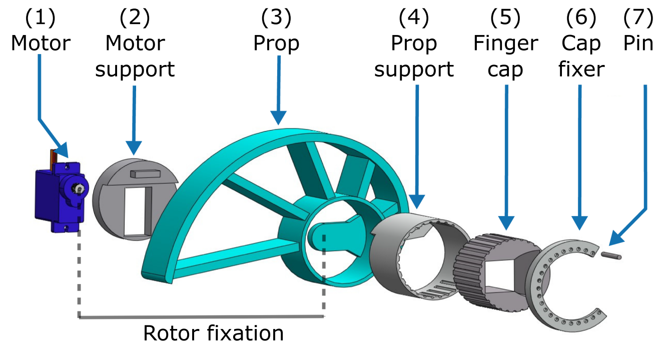

Fig. 4. The different parts of the Snail, including the actuator (1), the prop (3), and the thumb cap (5).

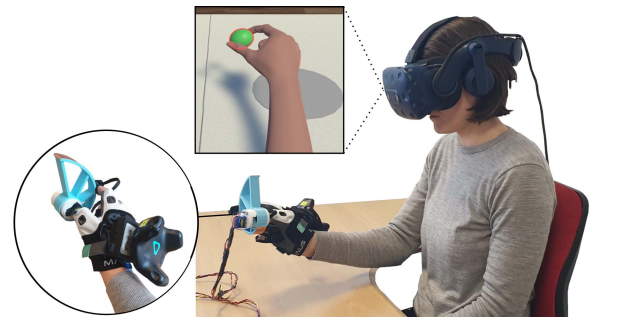

Fig. 5. The Snail is integrated into VR- environments using a VR headset, a hand tracker, and a tracking glove.

is fixed in a motor support (2) fixed on the prop support (4). The user's thumb is inserted in a cap (5), inserted in the prop support (4), and fixed with a cap fixer (6). The cap is personalized for each user so the thumb does not rotate. The surface in contact with the thumb fingerpad is flat, and room is left for the finger tracking system (see Section III-D). The orientation of the cap is calibrated for each user to compensate for the natural orientation of the thumb. To do so, the finger cap (5) can rotate inside the prop support (4) and is blocked with a pin (7) so it can be adapted to each user.

The correct orientation of the finger cap is determined during a calibration phase. In this phase, the Snail interface displays a grasping size of 4 cm, and a mark indicates where the user's finger should make contact. Users are instructed to grasp the interface multiple times, and the finger cap is rotated until the index finger aligns with the mark on the interface.

The parts are 3D printed with ABS material (precision 0.016 cm, filling rate 40%). The prop (3) and the prop support (4) are printed in the appropriate direction to create a smooth texture between them and avoid friction during rotation. The overall interface weighs 55 g.

The motor (1) is a small and low-power servomotor (*9 G*, torque: 1.8 kg.cm, weight: 9 g, precision: 1°, speed: 0.1 sec/60°, stall current: 750 mA@4.8 V). Its maximum angle is 180°, so it can display all the grasping sizes. From (1), the command motor θ depending on the grasping size gs can be deduced with the formula :

$$gs = \sqrt{x^2 + y^2} \quad \text{and} \quad \theta = (\log(gs) - \log(a))/\log(b) \qquad (2)$$

C. Sensors and Control

The servomotor already integrates a position control. Sensors were added to detect the grasping and the force exerted by users on the interface. The grasping is detected by a capacitive sensor consisting of copper tape applied on the prop and 1 MΩ resistor (Fig. 2). The force applied by the finger on the prop is measured with a resistive sensor *FSR 402 Interlink* (min force: 0.2 N, max force 15 N), combined with a 10 kΩ resistor. Forces were deduced from a non-linear equation provided with the resistive sensor for 10 kΩ. The validity of this equation was verified using weights.

The sensor is placed at the thumb pad level since measuring the force at this location is easy, and the contact is stable (Fig. 2). The actuators and sensors are connected to a computer by an *Arduino* microboard (max power: 40 mA@5 V).

D. Integration Into VR-Environments

The Snail interface is implemented in VR using Unity software (version 2022.3.16f1) and a VR headset (*HTC Vive Pro*) that displays a 3D immersive view of the virtual objects. The overall simulation runs at a frequency above 90 Hz.

The user is represented by a virtual hand with only the index and thumb fingers moving. The hand's position is tracked by a wireless *HTC Vive* tracker and two external lighthouses. The movements of the fingers are tracked by a *Manus Quantum* glove connected wirelessly to the computer (Fig. 5). The glove comes with an inverse kinematics (IK) algorithm that reconstructs the complete finger position to simulate the hand naturally. The cap of the Snail is designed to fit the user's thumb wearing the glove. The glove induces friction when the index finger contacts the Snail surface, which could have been detrimental to the interaction, particularly to the softness simulation. These forces were then limited by covering the glove index pad with a copper surface.

1) Manipulation: During manipulation, the Snail rotates to display a grasping size matching the size of the virtual object being grasped (Fig. 1(b)). If the user is not grasping, the Snail remains in its minimal position. When the user is grasping, the Snail must be pre-positioned to display convincing feedback when the user finally encounters the interface. The distance between the hand and the virtual object is monitored, as well as between the thumb and index fingers. If the hand is close to a virtual object ($d < 5$ cm) and the thumb/index finger distance is larger than the object size, i.e., if the user initiates the grasping, the Snail positions at the correct position. When the user closes its grasp, he then feels the correct size.

Virtual objects (including the virtual hand) have colliders to detect virtual grasping. When a collision between a virtual object and the virtual hand is detected, and the capacitive sensor on the Snail is triggered, the virtual object is grasped. It becomes a child of the virtual hand so that it follows its movements. A red outline around the object confirms this state. If the real index finger releases the Snail, the capacitive sensor is no longer triggered, and the virtual object is released. The user's real index finger moves away from the surface of the Snail when releasing the virtual object, so the haptic interaction is realistic. Moreover, the capacitive sensor is fast enough to ensure that the virtual object also releases and does not stick to the virtual hand. The Snail then positions in its minimal position.

This method of integration is versatile. It allows the simulation of haptic feedback corresponding to any virtual object as long as the simulation knows its size.

2) Softness Exploration: The Snail renders high stiffness when being static to display a grasping size. To simulate soft objects, it rotates depending on the force users exert on the prop. The grasping force is inferred using the FSR sensor, and the penetration distance is calculated according to a linear elastic model with Hooke's Law, depending on the simulated material. The Snail interface moves to simulate the corresponding grasping size. To provide visual feedback, the virtual object deforms in the direction of the grasp (Fig. 1(c)). The deformation is limited by a maximum penetration for more realism and to avoid exceeding the Snail interface's grasping size limit of 1.5 cm, particularly for small objects. This integration method is versatile and can simulate a variety of soft feedback.

IV. Technical Evaluations

The Snail's technical features have been studied to understand its characteristics better. The prop should be able to resist high forces without breaking or deforming to provide convincing rigid feedback. The active actuator should allow simulating force feedback that corresponds to soft objects. Finally, since the actuator doesn't directly counteract the grasping force, the power consumption should be low to increase the battery's operating time and portability.

A. Rigid Feedback

The prop's stress and strain (deformation) were calculated using mechanical simulation software *Solidworks*. We conducted a static study for an applied force of 100 N. This value was chosen to compare with the performance of existing interfaces based on brake systems [4]. The contact between the prop and the prop support was considered rigid, so only the stress and deformation of the prop were examined. The material used for the prop was plain PLA with a stress fracture of 73 MPa, which has lower resistance than the ABS (Acrylonitrile Butadiene Styrene) material used for printing the prop. We applied a force of 100 N at different points of the structure, from the exterior surface towards the center. The contact surface representing the finger was approximated by a force distribution on a circle of 1 cm^2.

The analysis results for 3 contact areas are shown in Fig. 6. The last 2 contact areas are considered more sensitive because they were applied on the Snail's tail. Despite the printed prop not being plain, the stress is still below the stress fracture coefficient of 73 MPa. Additionally, the deformation remains very low, with a stiffness around 1800 N/cm. A safety factor of 1.5 was applied to guarantee that even with approximation in the model, these values are not underestimated. The prop could be filled with more material to increase stiffness if necessary.

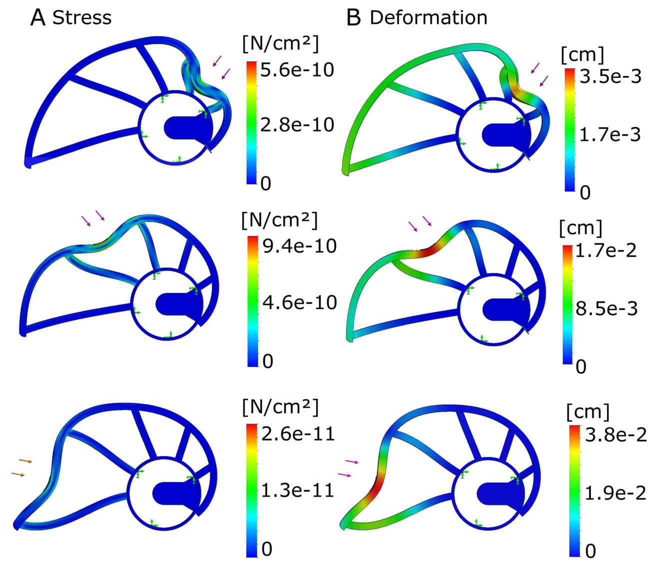

Fig. 6. Stress (A) and deformation (B) of the prop for 100 N of applied forces (represented by red arrows) on 3 different areas. Deformations are exaggerated in the images to help visualization.

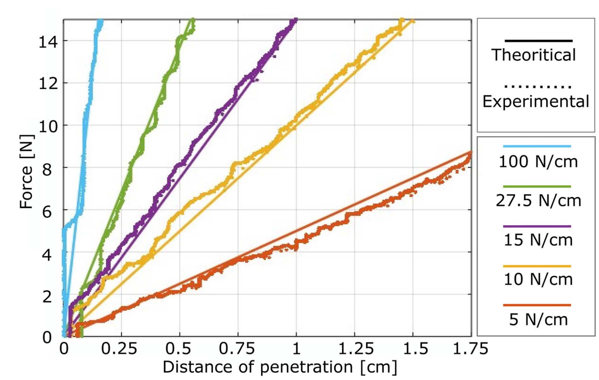

Fig. 7. The five levels of softness from 5 N/cm to 100 N/cm simulated from a linear elastic model.

B. Soft Feedback

A set of 5 levels of softness ranging from 5 N/cm to 100 N/cm has been investigated, which is similar to the ones tested by the Claw [6] (Fig. 7), except 2.5 N/cm that was not investigated due to limitations of the force sensors. We simulated the different softnesses with the method presented in Section III-D2. The prop rotation was inferred in real-time using a potentiometer *P160KN* (resolution: 0.29°) and another *Arduino* micro board communicating at more than 3 kHz. It was then converted to a distance of penetration.

In Fig. 7, we can observe that the experimental softnesses are consistent with the theoretical softnesses, following the same with minor deviations. The influence of such simulations on the user's perceived stiffness is explored in Section V-B.

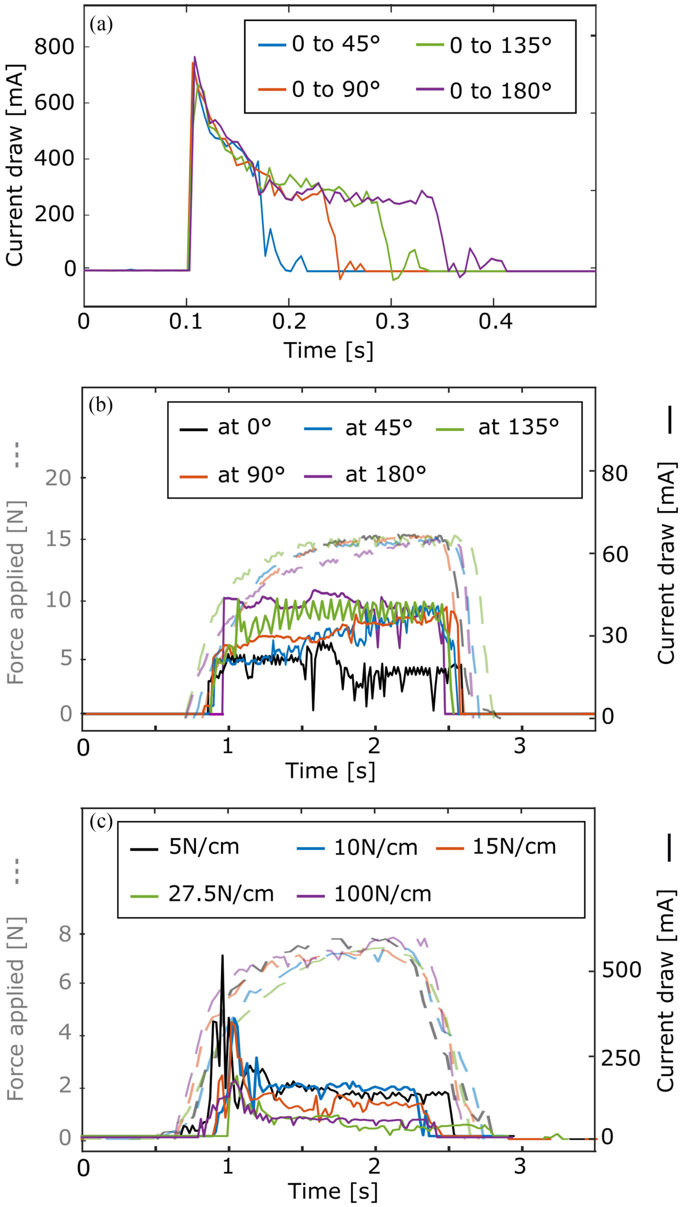

Fig. 8. Current drawn by the Snail when positioning (a), when being grasped by users (b), and during softness simulations (c). Dot lines represent the forces, and plain lines represent the current. Rotations of 0°, 45°, 90°, 135° and 180° correspond to 1.5 cm, 2.4 cm, 3.5 cm, 5 cm and 7 cm grasping sizes.

C. Power Comsuption

The current drawn by the actuator was measured using a current sensor (*INA219B*, resolution: *0.8* mA, max current: *3.2* A) and an Arduino board communicating at 3 kHz. It was first measured when the prop rotated to display different grasping sizes (Fig. 8(a)). The interface drew a peak current of 750 mA at the start, which aligns with the actuator's characteristics described in Section III-B. The current quickly decreased and stabilized at 300 mA until it reached its position.

The current was also measured while users held the Snail interface at different positions (Fig. 8(b)). A user was asked to squeeze the interface hard, and the force was recorded using the FSR sensor, while the current was measured using the same sensor as before. The force sensor saturates at 15 N. The current remains below 60 mA for all grasping positions, with some fluctuations due to the interface holding its position. The increase in grasping size leads to a slight increase in current, likely due to increased instability in these positions.

Finally, the current was measured during softness simulations (Fig. 8(c)). A user was asked to continuously squeeze the interface to simulate different levels of softness. The figure shows that higher softnesses resulted in slightly higher currents, as the Snail had to move more during these simulations. A peak current is observed when the user starts to squeeze, as this initiates the interface motion. Apart from the peak, the current remains below 200 mA, confirming that only a small amount of power is drawn.

D. Summary of Technical Features

The technical features of the Snail are presented in Table I and compared to other existing interfaces. Grabity [8] is not presented since it is similar to Wolverine [4], and technical features were not specified in the dedicated paper.

The Snail interface weighs 55 g, which is reasonable compared to existing wearable haptic interfaces on the fingertip [3] and similar to Wolverine [4]. The Snail interface has a unique operating mode that enables it to transmit continuously high force feedback (>100 N), which is equivalent to brake-based interfaces [4]. Forces during grasping (e.g., [39]) or exploration tasks (e.g., [40]) do not reach 100 N, but can reach more than 30 N and the Snail can handle such feedback. The Snail rigid feedback is also characterized by high stiffness, greater than 1800 N/cm. In contrast, the Gripper [7], the other wearable haptic device that uses a direct actuator, cannot render forces exceeding 2.7 N.

An important consideration is the duration of interactions. Interfaces that rely on peak forces (such as the Claw [6]) cannot sustain a command for a long time without risking damage to the actuator. On the other hand, grasping forces exerted on the Snail are independent of the actuator forces, allowing for long simulated interactions. Additionally, the Snail draws less energy since its current remains below 300 mA during positioning (small time) and below 60 mA grasping.

The technical evaluations show that the interface can simulate different softnesses from 5 N/cm to 100 N/cm, which is complicated with brake-based interfaces such as Wolverine [4]. This can be achieved again with a small power draw, less than 200 mA on average.

Finally, compared to some other interfaces, the Snail is easy to replicate. However, the tracking is not embedded, and an external device is required to get finger positions (e.g., *Manus Quantum glove*).

V. User Evaluations

User evaluations were conducted to assess how users perceived the haptic feedback displayed by the Snail. The first two experiments evaluated users' perception of haptic feedback corresponding to different grasping sizes and softness levels.

TABLE I
TECHNICAL FEATURES OF THE SNAIL COMPARED TO OTHER STANDARD PORTABLE HAPTIC INTERFACES

	The Snail	**Gripper** [7]	**Wolverine** [4]	**The Claw** [6]	**Capstancrunch** [2]
Mounting	Wearable	Wearable	Wearable	Hand-held	Hand-held
Grasping type	2 fingers	2 fingers	4 fingers	2 fingers	2 fingers
Grasping size	$1.5 - 7cm$	Full range	$2 - 16cm$	Full range	Full range
Actuation	Direct	Direct	Brake	Direct	Direct/Brake
Maximum force	$> 100N$ (continuous)	$2.7N$ (continuous)	$> 100N$ (continuous)	$30N$ (peak)	$20N$ (peak)
Stiffness	$> 1800N/cm$	-	$1620N/cm$	$57.3N/cm$	$58.8N/cm$
Softness	Yes	Yes	No	Yes	Yes
Power draw	$300mA@5V$	$857mA@4.2V$	$780mA@3.7V$	$1A@5V$	- (Small)
Weight	$55g$	-	$55g$	$335g$	-
Replication	Simple	Simple	Complex	Complex	Complex
Fingers tracking	External (Tracking glove)	Embedded	Embedded	Embedded	Embedded

Cells colored indicate interesting properties. When the parameter is not known, "-" is indicated. The softness capability was deduced from the type of actuation.

They were conducted outside of VR to test the Snail's capabilities alone without visual feedback. The third experiment integrated the interface into VR to test its impact on the complete user experience. The ethical committee from the Inria Rennes research center approved all the procedures.

A. Experiment 1: Perception of Grasping Size

Experiment 1 aimed to test the ability of users to differentiate between different sizes of rigid objects using the Snail interface. Grasping size perception of objects has been investigated before (e.g., [29]). However, the prop was not worn on a finger in these studies. The Snail is fixed on the thumb so that it rotates with it when grasping, so the grasping size depends on the finger's kinematics, which changes depending on the object size and can vary between two grasps of the same object. This experiment then also aims to verify the repeatability of the grasping motion with the Snail interface.

A two-alternative forced choice (2AFC) method was used, where participants interacted with two grasping sizes simultaneously and had to choose the larger one. This process was repeated multiple times for different pairs of stimuli. The participants were required to test 12 different stimuli ([1.5 cm, 2 cm, 2.5 cm, 3 cm, 3.5 cm, 4 cm, 4.5 cm, 5 cm, 5.5 cm, 6 cm, 6.5 cm, 7 cm]) within the interface's lower and higher boundaries. To avoid too many comparisons, a stimulus was compared with the nearest stimuli with 0.5 cm, 1 cm, and 1.5 cm shift, and each comparison was made five times. In total, a participant performed 165 comparisons distributed in three blocks, each taking approximately 10 minutes to complete. The order of stimuli appearance and the blocks were randomized to avoid bias.

The finger cap of the interface was adapted to the participants' thumb sizes and calibrated to compensate for the natural orientation of the thumb (see Section III-B). The participants' hands were hidden under a box to prevent them from seeing the interface during the experiment. Participants could have guessed if the size between the 2 stimuli was increased or decreased by feeling the prop's moment of inertia due to rotation. To avoid this bias, we displayed random rotation for one second between stimuli and changed starting points for each stimulus. Logarithmic spirals have the interesting property of a constant slope angle, limiting the influence of the shape of the prop on the distance estimation.

TABLE II
RESULTS OF THE SIZE COMPARISONS FOR RIGID GRASPING IN EXPERIMENT 1

Size (Δ)	**Δ + 0.5 cm**	**Δ + 1 cm**	**Δ + 1.5 cm**
$1.5cm$	$88.3\% \pm 10.2$	$96.6\% \pm 7.8$	$98.3\% \pm 5.7$
$2cm$	$87.3\% \pm 7.7$	$95.7\% \pm 7.7$	$97.2\% \pm 9.6$
$2.5cm$	$90\% \pm 13.4$	$93.3\% \pm 9.8$	$96.6\% \pm 9.6$
$3cm$	$68.8\% \pm 15.5$	$95.8\% \pm 9.7$	$97.9\% \pm 7.2$
$3.5cm$	$80\% \pm 17.5$	$96.6\% \pm 7.8$	$94.5\% \pm 9.8$
$4cm$	$88.3\% \pm 10.3$	$95\% \pm 9$	$100\% \pm 0$
$4.5cm$	$91.7\% \pm 13.4$	$96.7\% \pm 7.8$	$98.3\% \pm 5.7$
$5cm$	$81\% \pm 15.8$	$95\% \pm 9$	$98.3\% \pm 5.7$
5.5 cm	$85\% \pm 9$	$98.3\% \pm 5.7$	$91.6\% \pm 10.3$
$6cm$	$76.6\% \pm 16.7$	$93.3\% \pm 9.8$	$\sim$
$6.5cm$	$68.8\% \pm 24.1$	$\sim$	$\sim$
Total	$82.4\% \pm 8.1$	$95.7\% \pm 1.5$	$97\% \pm 2.4$

For each comparison, the mean percentage of correct answers and standard deviations of all the participants are given. Comparisons that were on the limit of the interface and could not be tested are indicated by the symbol "$\sim$".

Participants used keyboard inputs to switch between stimuli and answers. Once they moved to stimulus 2, they were not allowed to test stimulus 1 again. The computer screen only displayed "Stimulus 1", "Stimulus 2", and "Which stimulus was larger?".

A panel of 12 volunteers (3 women, age $= 27.2 \pm 4.2$ years) participated. They declared being right-handed and had no physical issues that could have been detrimental to the experiment. The percentages of right answers for each comparison are displayed in Table II.

The participants could discriminate well between all pairs of stimuli, with correct answers above the chance level of 50% and small variabilities. They could even discriminate size with a minimal difference of 0.5 cm, although the mean correct answer for this shift was slightly lower than for 1cm and 1.5 cm differences. Some comparisons were slightly lower than the accepted 75% threshold for the 0.5 cm difference, probably because of kinematics variations (even small ones) for these sizes. But overall the results confirm that two fingers exhibit stereotypical movements when grabbing an object, allowing for repeated size differentiations. They also showed that the participants had some difficulty with larger grasping sizes, particularly with a 6.5 cm size and 0.5 cm shift. After the experiment, some participants mentioned that they had difficulty grasping the larger size due to their small finger spans. This finding suggests that if large objects are used in VR, these users may face similar difficulties, so the lack of haptic feedback for this size is not a significant issue.

In summary, the results of this experiment provide evidence that the Snail interface is effective in displaying haptic force feedback for different sizes of rigid grasp. They are also the first proof that the Snail interface is usable by different users.

B. Experiment 2: Softness Perception

Experiment 2 aimed to test the ability of users to perceive different softness with the Snail interface. Participants were asked to rate five softnesses ([5 N/cm, 10 N/cm, 15 N/cm, 27.5 N/cm, 100 N/cm]) on a scale of 0 to 100, where 0 represented "Very soft" and 100 represented "Very hard". The softnesses were rated for four different initial grasping sizes ([2.5 cm, 3.5 cm, 4.5 cm, 5.5 cm]) to test the sensation for different sizes of virtual objects. The initial size of 1.5 cm was excluded from the experiment as it was impossible to display soft feedback from this size. Additionally, 6.5 cm was found too large for some users in the first experiment (see Section V-A), so it was assumed that if the softness was correctly perceived for other sizes, it would work for this size as well.

The finger cap of the interface was adapted to each participant in the same way as in Experiment 1 (Section V-A). The same hardware and method as in Section IV-B was used to simulate the softnesses. The participant's hands were hidden under a box to avoid bias from visual cues of the interface. The participants used a keyboard to control the different stimuli, and they could switch between them. They rated the softness of each stimulus using sliders displayed on the screen, which were initially set at 50. The initial order of stimuli was randomized across participants but then the sliders were ordered in real-time so that the one with the higher value was displayed at the top, making it easier for participants to switch between sliders with approaching values. Participants could then test again and update the slider values as long as they wanted. This protocol allowed to test discriminations in a scenario where users can test softnesses several times before making a decision. Participants completed the overall procedure once.

A panel of 12 volunteers (5 women, 27.7 ± 4.5 years) participated in the experiment. They declared being right-handed and had no physical issues that could have been detrimental to the experiment. The participants were different from Experiment 1. The results are presented in Fig. 9.

The results follow the same trend for all the initial grasping sizes and present small variabilities.The normality assumption was tested with Shapiro-Wilk, and was not met for some data. Friedman test was then performed to assess the impact of softness on the rankings and post-hoc tests were performed using the Wilcoxon signed-rank method. The Friedman test confirmed the effect of displayed softness on the perception of softness ($p < 0.001$). Post-hoc tests showed that all softnesseses were ranked correctly ($p < 0.001$), so participants could correctly discriminate all of them. Participants perceived low softness (100 N/cm), so hard stimulus, as very rigid, confirming the Snail's interest in presenting such feedback. The interface could also display different soft feedback, even very soft ones (e.g., 5 N/cm).

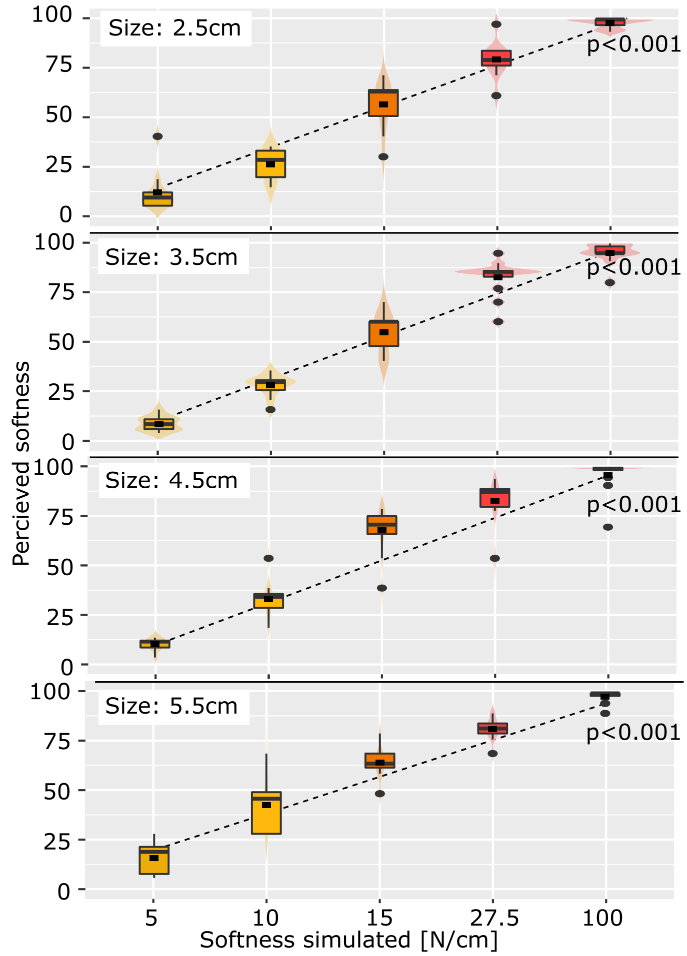

Fig. 9. Results of the softness comparisons in the experiment 2. The average values and dispersion are displayed with boxplots for the different initial sizes and softnesses. A value of 0 represents a "very soft" feedback, and a value of 100 represents a "very hard" one.

Overall, the results of this experiment suggest that the Snail interface can simulate haptic feedback corresponding to different softnesses.

C. Experiment 3: User Experience in VR

Experiment 3 evaluated the quality of the user experience and performances with the Snail interface in VR. The participants were provided with visual and haptic feedback. The Snail interface was compared to commonly used vibrotactile feedback in two typical tasks: manipulation (pick and place) and exploration (softness).

The vibrotactile feedback was delivered via two f linear resonant tactors (1 G, 70 Hz) placed on the thumb and index fingertips. An *Arduino micro* board controlled the tactors at a frequency around 1 kHz. The tracking system and the Snail integration described in Section III-D were used.

1) Manipulation: Participants were asked to perform a pick-and-place task in which they had to grasp various virtual objects and move them from one plate to another. These plates had a circumference of 20 cm and were located 20 cm from each side of the users and 30 cm in front. To test different grasping

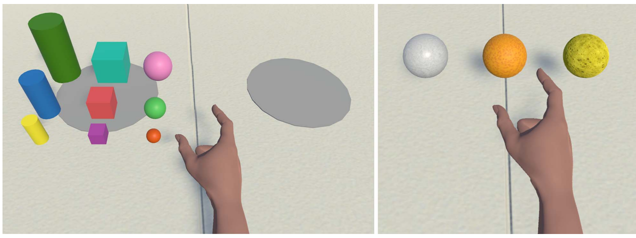

Fig. 10. The different virtual objects displayed in the manipulation task (Left) and the exploration task (Right). During the experiment, only one object was shown at a time.

sizes and determine whether the shape of the virtual objects affected the user experience, 9 types of objects were displayed: 3 shapes (cube, cylinder, and sphere) x 3 sizes (2.5 cm, 4 cm, and 6 cm) (Fig. 10). These shapes were displayed consecutively. The grasping was detected when both the thumb and index finger collided with the virtual object, and the object was released when the index finger was not colliding anymore. The Snail interface displayed the size corresponding to the current virtual object when the participants were closed from it (see Section III-D). In the vibrotactile condition, vibrations were displayed for $0.5s$ when both fingers were in contact. It took around 3 minutes to complete the simulation.

2) Exploration: In a second task, participants were asked to explore different levels of softness. The task involved a sphere of 5.5 cm displayed in the center of the environment, with three different visual textures available (marble, orange, or sponge), each corresponding to a different level of haptic softness (100 N/cm, 20 N/cm, and 7.5 N/cm, respectively) (Fig. 10). Participants were allowed to squeeze the sphere for 10 seconds when a texture was displayed, with each texture displayed 3 times in a random order for a total of 9 repetitions. The Snail interface displayed the softness values corresponding to the texture displayed. In the vibrotactile condition, vibrations were displayed as long as the virtual shape was changing shape, resulting in longer vibrations for soft objects. The task took approximately 2 minutes to complete.

After each task and feedback, the quality of the haptic user experience was rated by the participants using the questionnaire proposed by Anwar et al. [41]. The questionnaire comprised 11 questions grouped into 4 factors: realism, harmony, involvement, and expressivity. The participants answered each question on a 5-point scale, and the score by factors was computed using the method described in the paper (including factor loadings). At the end of the experiment, the participants evaluated the usability of the Snail interface with the SUS questionnaire [42]. It consists of 10 questions rated on a 5-point scale. The total score was computed using the method described in the paper. The time taken to complete a trial and the number of times an object was lost (released and re-grasped) were inferred to measure the performances.

A panel of 12 volunteers (4 women, 26.2 ± 3.2 years) participated in this experiment. The participants were different from the Experiments 1 and 2. Four of them declared to be left-handed.

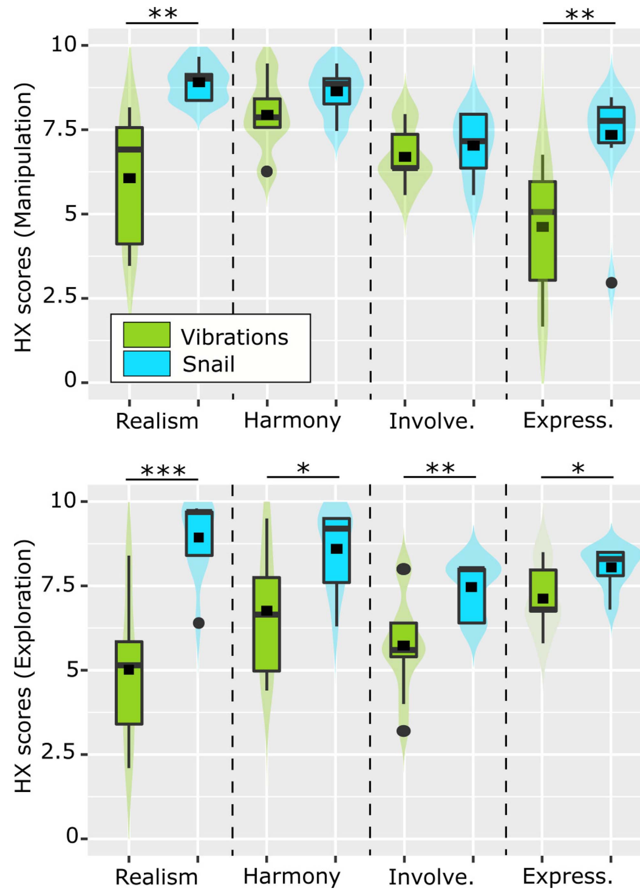

Fig. 11. The results of the haptic experience questionnaire for vibrations and for the Snail in the manipulation task (Top) and in the exploration task (Bottom). Higher is better for all these measures. The symbol “$*$” stands for $p < 0.05$, “$**$” for $p < 0.01$ and “$***$” for $p < 0.001$.

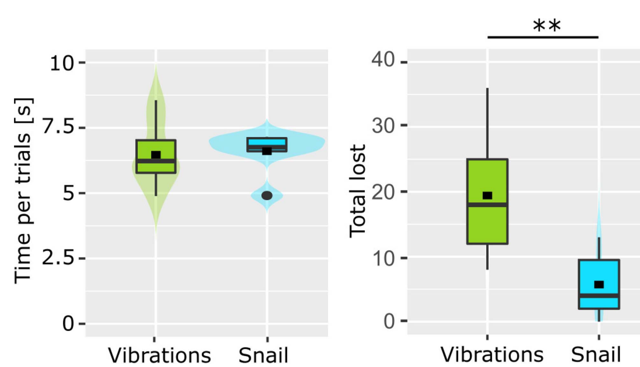

Fig. 12. Mean time per trials (Left) and the number of objects lost during the manipulation task (Right). Lower is better for both measures.

They had no physical issues that could have been detrimental to the experiment.

The results for the haptic experience are presented for the manipulation and exploration tasks in Fig. 11. The results for the performances are displayed in Fig. 12. Scores were compared between vibrotactile feedback and the Snail. The normality assumption was tested with Shapiro-Wilk, and if it was met, these data were analyzed using Student’s t-tests. Non-parametric

TABLE III
THE RESULTS OF THE SUS QUESTIONNAIRE

	Question	Score (Avg. $\pm$ Std)
(Q1)	Use this system frequently	3.5 ± 1.0
(Q2)*	Unnecessarily complex	1.6 ± 0.7
(Q3)	Easy to use	4.1 ± 0.8
(Q4)*	Need support to use the system	2.4 ± 1.1
(Q5)	Functions well integrated	4.4 ± 0.6
(Q6)*	Too much inconsistency	1.6 ± 0.8
(Q7)	Would learn quickly	4.3 ± 0.6
(Q8)*	Cumbersome to use	2.8 ± 0.8
(Q9)	Confident using the system	3.7 ± 0.5
(Q10)*	Need to learn a lot	1.5 ± 0.5
Total	~	**75±18.9**

Higher is better for thequestion without "$*$", and lower is better for others.

analyses using the Wilcoxon signed-rank test were performed for the other data. Holm-Bonferroni correction was applied to tackle the issue of multiple hypotheses testing. We checked the results of the left-handed participants, and none of them were outliers so they did not differ significantly from the results of the right-handed participants.

In the manipulation task, the realism was significantly higher with the Snail than with the vibrations ($Z = -3.06$, $p = 0.002$, $d = 1.48$). The expressivity was also significantly higher with the Snail ($Z = -2.9$, $p = 0.003$, $d = 1.24$). Concerning performances, the number of losses was significantly lower with the Snail ($t(11) = 5.3$, $p = 0.002$, $d = -1.29$). In the exploration task, all 4 factors were significantly higher with the Snail interface than with the vibrations: realism ($Z = -3.06$, $p < 0.001$, $d = 1.52$), harmony ($Z = -2.4$, $p = 0.018$, $d = 1.06$), involvement ($Z = -2.69$, $p = 0.007$, $d = 1.22$) and expressivity ($Z = -2.4$, $p = 0.015$, $d = 1.01$). The scores for the SUS questionnaire are displayed in Table III. The total score is above 68, demonstrating the usability of the Snail interface.

Overall, the results confirm the Snail interface's interest and usability in VR simulations for manipulation and exploration tasks.

VI. Discussion

A. Validation of the Snail Concept

The Snail is based on the idea that a single prop could represent virtual objects of various sizes and shapes, which was validated by user experiments. Experiment 1 showed that participants could efficiently perceive different grasping sizes. Although the prop's curvature is perceivable [43], Experiment 3 showed that a perfect match is not necessary between the prop and virtual objects to achieve realistic feedback. This was true even when cylinders and spheres of different sizes (i.e., of different curvatures) or cubes (i.e., flat surfaces) were grasped.

Additionally, we hypothesized that the Snail could simulate convincing rigid force feedback for low-power actuation. This idea was also validated through user experiments. The technical evaluation results show that the prop can withstand high forces (> 100 N) with minimal deformation. The interface also draws power for a short time during positioning but draws small power during grasping. Experiment 2 scores close to 100 for 100 N/cm, and Experiment 3 scores on realism indicate that the feedback was realistic, validating the concept. This ensures low power consumption, which is critical for guaranteeing the interface's autonomy (use of a battery for an extended period) and portability (weight of the actuator).

We postulated that the Snail could simulate soft objects by rotating the prop when squeezed. Different techniques have been investigated in the past (e.g., vibrations [35] or skin stretching [37]), but our technique allows us to mimic the finger penetration in the soft object. The technical evaluation and Experiment 2 validate the use of the actuated prop as a means of rendering different softnesses.

The interface acts as an encounter-type display, so its speed is an essential factor. The technical evaluation showed that the small servo motor was fast enough to move the display in less than 0.4 seconds. In Experiment 3, participants were not given any specific instructions on how to interact with the display, but they still found the experience realistic. Some participants even reported being impressed by how quickly the interface could rotate. Overall, these results show that the Snail is adapted to unconstrained real-time interactions.

Finally, the Snail prototype comprises only 3D-printed parts, a low-cost servo-motor and force sensor, an Arduino board, and a capacitive sensor (i.e., copper tape and a resistor). Effective haptic feedback can then be rendered with a low-cost interface that can be easily reproduced and multiplied.

B. Interests for User Experience

The Snail system was used in 3 different experiments, and it received SUS scores above 68, demonstrating its usability in manipulation and exploration tasks. Participants found the system very easy to use (Q3), the functions well-integrated (Q5), and thought they could learn how to use it quickly (Q7).

The first interest of the interface is to help explore virtual object properties. Experiment 1 showed that it allows discrimination between different grasping sizes, even with a 0.5 cm difference. Experiment 2 showed that it allows discrimination between different softnesses. Finally, it helps the manipulation of virtual objects, avoiding losing them during transport (Experiment 3), and the time to perform the task was not significantly different from the one with vibrations.

The Snail also enhances the user's experience in VR compared to vibrations. Scores for the haptic experience show that the Snail feedback was perceived as more realistic and expressive. Scores for vibrations were relatively high for the Harmony factor, which is unsurprising considering they display coherent haptic feedback (impulsive feedback) when users contact an object. However, some participants reported that the Snail feedback was more coherent during the moving phase and provided more information on the size of the object being grasped, explaining the scores for realism and expressivity. During the exploration of softness, the Snail was also considered more realistic, harmonious, and expressive than the vibrations. In addition, it increased users' involvement to some extent.

In summary, the Snail shows several interests in enhancing VR interactions but not only. In Experiments 1 and 2, participants could distinguish between different sizes and softness with haptic feedback alone. This indicates that the Snail interface has potential in scenarios with low visual feedback, such as teleoperation or complex scenes with virtual objects partially hidden.

C. Current Limitations of the Prototype

The Snail prototype worked well, and enhanced interactions, but some issues could be tackled to improve it.

Some participants reported that the fingerpad did not fit well with their thumbs, disturbing their experience. The fingerpad could be adapted to better fit some users' thumbs by designing personalized prints for greater comfort. Some participants also reported that the interface was a bit heavy, as supported by the question (Q8) of the SUS questionnaire. The prop could be printed with a lower filling rate as its current version supports high forces. The prop size could also be reduced for some users, as the first experiment's results suggest that the maximum grasping size (7 cm) is too large for some people or for applications that do not involve large objects.

Some participants' feedback of the SUS (Q4) indicated that the interface is a bit difficult to use for them. This difficulty may have stemmed from the calibration process, which some found to be lengthy. However, it only needs to be done when changing users. As the Snail interface is easy to replicate, a version for each user could effectively address this issue.

The algorithm used to predict the grasping size in VR is still relatively straightforward. By implementing more advanced algorithms (based on raycasting or eye tracking for instance), the interface could be positioned in advance and more smoothly at the correct position, improving the user experience. Furthermore, shapes with varying grasping sizes, such as cone or bottle shapes, could be simulated.

In the future, it would also be interesting to compare the Snail with a force feedback interface (e.g., Grabity [8]). More fine vibratory feedback could also be tested, especially for the softness exploration. In the experiment, linear resonant actuators were used, so softnesses were simulated by changing the durations of vibrations. The Snail could be compared with more advanced vibrotactile actuators displaying finer signals.

Finally, the Snail is currently connected to the computer and powered with wires but could become portable. It draws very little power, so it can be fed by a battery for a long time, and Wi-Fi or Bluetooth be used for communication.

D. Future Directions of Research

The idea of the actuated prop to display grasping feedback may pave the way for further designs and use of the interface.

We limited friction/tangential forces by covering the index pad with a copper surface so it could slide smoothly on the surface of the Snail, in particular in softness simulation. Results show that the softness detection was then completely performed on the variation of finger distance during grasp. The Snail could display friction by removing or changing the cover so that softness perception would be combine grasping size and tangential forces. It could contribute to even better perception since previous work demonstrated that friction can simulate holes or bumps [44]. A challenge would be to find suitable friction to allow finger slip of any type of finger.

An advanced version of the interface could also integrate tactile feedback (e.g., vibrations, warmth with Peltier cells) as it is simple to place elements into the structure. For instance, vibrations could increase the stiffness and softness perception even more than the Snail alone [34], [45]. In addition, the surface of the Snail is smooth, so it does not display texture information. Vibrations could then be added to display texture information and represent porous surfaces for instance.

Various shapes of the prop could also be investigated. For instance, haptic feedback could be displayed on multiple fingers. A possible solution is to make the prop look like a set of "stairs" with flat surfaces that allow grasping with several fingers, similar to Grabity [8]. This solution could be applied with redirecting finger technique [29] to display continuous sizes. The actuated prop concept could also be integrated into a controller to limit the weight and power drawn by current haptic VR controllers.

The interface could also simulate haptic feedback beyond grasping feedback. For instance, the inertial force generated by the rotating prop can be utilized to simulate the sensation of impact or weight by quickly shifting the rotation [28]. The prop can also stretch the index finger pad in different directions during exploration to simulate texture.

Finally the Snail could be tested in different VR environments and tasks. It could also be used by physiologists and neuroscientists to study hand perception and brain interpretation. For instance, depth cues were sufficient to provide a perception of softness in our experiments, and it would be interesting to explore this further.

VII. Conclusion

This paper introduced the Snail, a wearable haptic interface that renders force feedback when grasping objects in Virtual Reality. The Snail is based on a rigid prop that rotates around the user's thumb thanks to a small actuator.

The primary interest of the interface is to render convincing force feedback when grasping rigid virtual objects without the need for heavy actuation. The feedback can be simulated for objects of different sizes, ranging from 1.5 cm to 7 cm. Additionally, the interface can simulate various degrees of softness representing different materials.

Technical evaluations and 3 user experiments validate the effectiveness of the interface. The results indicate that the Snail can display different objects' haptic sizes and different softnesses. In terms of user experience, the harmony and involvement are similar to vibrations feedback, but the Snail improves performance, realism, and expressivity during manipulation. It also enhances realism, harmony, involvement, and expressivity during softness exploration.

The Snail unlocks the possibility of rendering convincing rigid force feedback and softness in Virtual Reality with a wearable interface, so it can be used in various applications.

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