Stiffness Simulation with Haptic Feedback Using Robotic Gripper and Paper Origami as End-Effector

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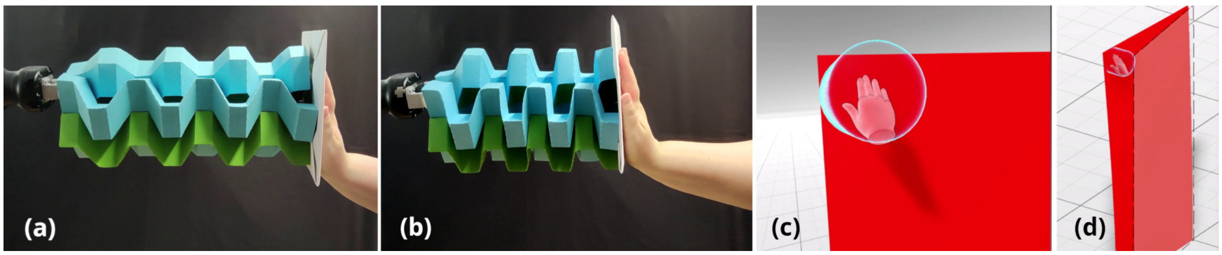

Figure 1: Stiffness simulation with our Zipper Flower Tube: (a) User's hand encounters uncompressed Origami, (b) hand presses against Origami, (c) user's view in VR while pressing against a virtual wall, and (d) side view on the virtual wall deformed from its normal state (shown in semi-transparent grey).

Abstract

Haptic feedback in Virtual Reality (VR) facilitates the transfer of virtual experiences into the physical world. In particular, haptic feedback in architectural design enables designers to feel the materiality of their creations, with the possibility to apply different materials, refine designs based on the haptic experience, and assess requirements at an early stage. In this paper, we assess an innovative end-effector based on an origami structure and a robotic gripper that can provide a real-time simulation of material elasticity and stiffness without requiring a prop change, offering a cost-effective and energy-efficient solution. The evaluation consisted of a perceptual study where participants used the origami end-effector and had to push a thin virtual wall in VR. We tested three types of stiffness rendering (Soft, Medium, and Stiff). Participants had to answer how stiff the rendering was and which type of material they could refer to when touching the virtual wall. Results showed that although the stiffness perception across conditions was not significant, participants reported different types of materials depending on the condition. We also discuss the potential of origami-based end-effectors for improving haptic interaction for architectural design in VR.

Keywords: Origami, encountered-type haptics, virtual reality, rigid-foldable tubes, material perception.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Virtual reality; Human-centered computing—Human computer interaction (HCI)—Interaction devices—Haptic devices; Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Empirical studies in HCI;

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1 Introduction

Providing haptic feedback in Virtual Reality (VR) can improve task performance and presence in a virtual environment by expanding the perception of virtual objects beyond their visual representation [24]. While haptics is a very active field of research, the existing approaches for general-purpose haptic interfaces tend to concentrate on mimicking the shape and size of virtual objects in the physical world. Yet, for higher fidelity haptic feedback, rendering mechanical behaviors of objects such as deformation and stiffness is necessary. For example, for the haptic rendering of a deformable wall or sofa in a virtual scene, the user expects to touch a deformable physical object in the real world to synchronize the tactile sensation with the visual input.

In certain applications, particularly those aiming to transfer experience from the virtual to the physical world like architectural design, feeling the materiality of elastic virtual objects can deepen the understanding of desired tasks [32]. Architects can apply materials with different stiffness properties and refine their designs, potentially improving them to better meet the client's or environmental requirements at an early stage. Additionally, dynamic haptic feedback in VR allows young designers and students to gain additional experience by seeing and feeling the dynamic behavior of each structure and material [7].

Although simulating such dynamic behaviors of objects using closed-loop control of robotic arms is feasible, it comes with significant challenges. The haptic device must swiftly respond while maintaining the capability for real-time stiffness adjustments, which adds an extra layer of complexity to the haptic rendering task.

Adjustable passive end-effectors can be designed as an enhancement of the robotic arms, capable of adapting to varying environmental conditions and object interactions without the need for complex control algorithms. This adaptability is crucial in scenarios where a high degree of responsiveness is required, whilst the computational load and mechanical complexity need to be minimized. By employing such end-effectors, the system can rely on their inherent mechanical properties to adjust to changes in force and stiffness, thus simplifying the overall control scheme.

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This paper presents a first evaluation of our innovative end-effector Zipper Flower Tube, introduced in a previous research paper [30], designed for a fast dynamic response based on a complex origami structure and a robotic gripper. Combining origami with minimal mechanical actuation created a flexible and responsive prop for dynamic, low-cost, and energy-efficient haptic feedback. It can simulate different material elasticity and stiffness in real time without requiring a prop change. We evaluated the performance of our origami end-effector through a user study.

2 Related Work

Numerous methods have been proposed to provide a haptic experience for immersed users. However, they all face particular challenges. Among prop-based haptic feedback solutions, the use of passive physical props resembling a desired virtual object, also known as “passive haptics” [16], was shown to deliver very realistic and robust haptic feedback [9]. It affords a substantial increase in realism in VR [12], which was also proven at large scales, e.g., a virtual pit [29] or even life-sized virtual environments [17]. The major shortcomings are the synchronization with the virtual environment (VE) and scalability, as passive props implicitly are not controlled by a computer and must be available in every form and every position required by the simulation.

In contrast, Encountered-Type Haptic Devices (ETHD) [10, 33] provide haptic sensations by placing a tangible end-effector at a desired location, using a robotic device, and waiting for the user to encounter it. ETHDs offer unconstrained free-hand contact with tangible objects, without keeping users in constant contact with the object as in common wearable haptic systems. ETHD actuators can be fixed on stationary platforms [18, 31], grounded on the user’s body [4, 11, 28], or mounted on mobile platforms like wheeled robots [20] or quadcopters [1], facilitating haptic experiences in large-scale walkable VEs. Mercado et al. provide a comprehensive survey on this subject [19].

While haptic feedback techniques primarily focus on simulating properties like shape, size, and texture, certain mechanical aspects, such as stiffness, remain underexplored. Soft object haptic rendering has proven effective in fields like medical VR [21]. Pseudo-haptic techniques [15] leverage visual dominance over haptics to manipulate the users’ perception and convey a sense of softness. However, there exists a consistency threshold for pseudo-stiffness methods in VR, limiting their applicability to a certain flexibility level [2].

In wearable haptic devices, some works address variable stiffness haptic rendering [23,27,34] but they are often limited to single-finger interaction, potentially impacting user immersion. Largilliere et al. [14] proposed a device for soft object haptic rendering with stiffness control, but it lacks support for full-hand interaction and real-time stiffness adjustments. Haptic Jamming [26] is a haptic display that simulates variable stiffness and deformable geometry via coffee grounds and air pressure. Another approach is Materiable [22], a pin-based shape display capable of rendering different stiffness and shapes. Although both devices allow full-hand interaction and real-time stiffness control, they also can be characterized by complexity, bulkiness, and high-cost structure. That makes them impractical for mounting on robotic arms for large-scale haptics. In comparison, our proposed approach offers a very low-cost, lightweight haptic display suitable for robotic arm integration.

Origami-inspired haptic props, which are getting increasingly popular [8, 13], provide simpler mechanical solutions with fewer actuators than pin displays or wearable haptic devices. Zuliani et al. [35] introduced a variable stiffness origami joint mechanism for haptic feedback, relying on the intrinsic stiffness of materials instead of the common closed-loop force control method [3]. Our proposed end-effector surpasses this by enabling real-time control of different stiffness within a single scene without requiring a prop change.

Exploring the use of a low-cost origami structure manipulated by a robotic gripper to simulate varying stiffness, from soft and highly flexible to semi-rigid, for unconstrained full-hand haptic interaction remains unexplored. Unlike prior work focusing on medical applications like touching soft tissues of the human body, we emphasize the architectural design domain, addressing user interactions with large-scale objects like walls and providing realistic haptic responses to applied forces.

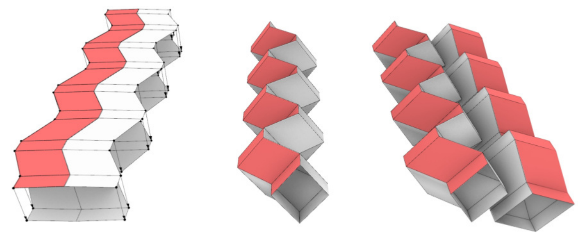

Figure 2: Zipper Flower Tube’s basis element: (Left) two flat pieces of a tubular element with connection points shown via arrows, (center) an assembled element in a half-folded state, (right) two congruent elements about to be connected via faces in a zippered fashion. By repeating the process of rotational zipper coupling, the final structure can be constructed. Note that, a row of faces in each step is marked in red as a hint to follow the orientation of the elements.

3 Study Setup and Environment

3.1 Zipper Flower Tube

Rigid-foldable origami has many applications, as it can be materialized by flat panels and rotational hinges. Foldable tubes, in particular, can be coupled in a zipper fashion (see Fig. 2) to increase the stiffness of the resulting structure while they expand [5]. This connection is used in the tubular flower, which consists of rotational congruent tubes with a deltoid cross-section [25]. A digital illustration of the model can be seen in Fig. 3. Due to their inherent reconfigurability and out-of-plane stiffness, tubular flowers exhibit a more robust cantilevering effect during expansion than alternative origami couplings [6]. Furthermore, their interlocking behavior in the expanded state distinguishes them from scissor structures and configurable springs. Our used Zipper Flower end-effector consists of five pedal tubes with 3.5 sections folded by 250 g/m^2 card stock. The total length of the Zipper Flower Tube during the expansion ranges between 17.5 cm to 33 cm with a cross-section of 17 cm. The thickness and the size of the card stock are specifically chosen to achieve a lightweight and durable result, which can be reproduced from pieces, cut by a regular desktop cutter plotter. Therefore, the final structure is sustainably reproducible from low-cost and recyclable materials. The resulting structure is robust enough to be utilized for dynamic haptic feedback. The high-stiffness collapsed and expanded states allow us to retain the pressure applied by the user and simulate the stiffness of various materials.

3.2 Mounting

The Zipper Flower Tube is actuated with a Hand-E Adaptive Gripper by Robotiq. We designed a custom mounting structure with FreeCAD and 3D printed it with PLA/PHA material. The resulting mount in Fig. 4 is fitted with a hook (a) on a supporting structure fixated on one gripper finger (b) to hold the paper origami straight. The mounting structure on the second gripper finger (c) is equipped with a ball bearing to allow the opening and closing of the Zipper Flower Tube. A lateral hook provides additional support to the origami. The whole assembly with the Zipper Flower on the mounting structure can be seen in Fig. 4d. The employed origami for our study was especially sturdy, long, and heavy. For that reason, we extended the fixed finger mount (Fig. 4b) with an additional support plate opposite

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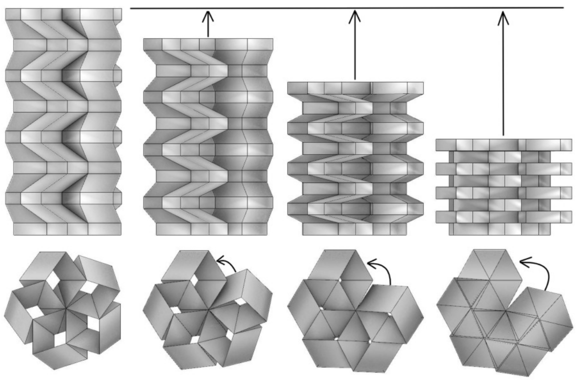

Figure 3: Expansion sequence of Zipper Flower Tube in four steps from right to left. Arrows illustrate the direction of the expansion in the top view (top), and the rotation of the cross sections in the front view (bottom). By fixing the positions of the tubes, additional resistance can be obtained.

Figure 5: Experimental setup at the conference.

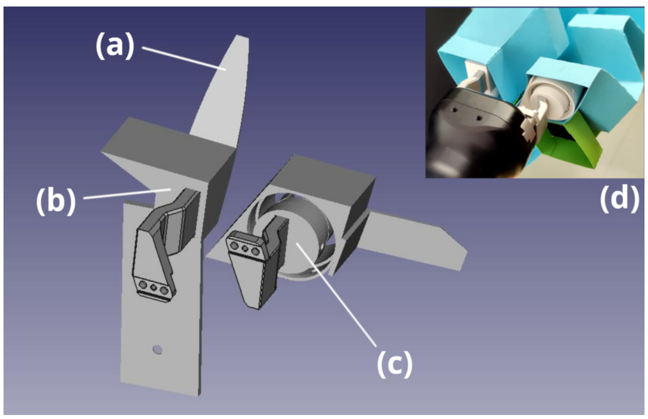

Figure 4: Gripper mounting of the Zipper Flower Tube: (a) Hook for origami, (b) gripper finger with fixed mount and downwards support plate, (c) gripper finger with rotating mount with ball bearing and side hook, (d) final assembly with paper origami mounted on the gripper.

to the hook, to give the paper structure further support and avoid sagging. On the other end of the Zipper Flower Tube, a painted white 20 cm by 20 cm cardboard panel was added for the haptic contact with the user. We fixated it inside the origami structure with a similar hook as in Fig. 4a.

3.3 VR Environment

We created a simple virtual environment with a floor and a wall enclosure around the user. In front of the participant, we placed a simple thin wall that changed colors to reflect the change of the material (green, blue, or purple), and gradually transitioned to red towards the maximum amount of deformation. The amount of deformation and the change in the sample wall's geometry were calculated to be bound to the force applied. We simulated three types of materials: **soft** with plastic deformation, **medium** with plastic-elastic deformation that recovered if no pressure was applied, and **stiff** with elastic deformation. The maximum deformation was 10 cm at a force of 10 N (except stiff). The medium material was simulated to resist before the pressure reached 5 N, at which the contracted fingers of the gripper spread, relaxing the origami. Only stiff was calibrated to deform 5 cm.

For the experience evaluation after each wall, we used a simple UI with a hand-interactive Likert-like scale with radio buttons and confirmation. For free-form questions, we showed the users a text field where the experimenter manually documented the oral answer. The participant's hands were visualized with a light-grey semi-transparent material accentuating edges, as shown in Fig. 1.

3.4 Technical Setup

The technical setup consisted of two computers connected using a gigabit network switch that ensured a low-latency wired connection between them. The Asus ROG Strix Scar 16 (i9 CPU, 32 GB RAM, and Nvidia RTX 4090) laptop with Windows 10 handled the hand tracking and rendered a virtual environment in Unity employing the HTC Vive Pro head-mounted display (HMD). For the hand tracking, we used an HTC OpenXR integration of camera-based tracking for the HMD, thus reducing the number of connected devices. The second computer is an ODROID N2+ single board computer (SBC), with Ubuntu-mate 18 and Robot Operating System (ROS) Melodic middle-ware installed. This SBC controlled the Robotiq Hand-E adaptive gripper and the FT-300 Force/Torque (F/T) sensor, and maintained data communication with the Unity laptop. Robotic devices were connected to the SBC via a USB serial connection. The F/T sensor was rigidly attached behind the robotic gripper and mounted on a table-mounted tripod at a height of about 1.5 m from the floor. The tripod was fixated on the table with a metal tension wire.

4 Participants and Procedure

The user study was run as a part of the demo at a conference (ACM SIGGRAPH 23, Los Angeles), where we showcased the concept of the origami end-effector for five days, six hours per day. Fig. 5 shows the actual setup and the simple virtual environment. We gave every participant an explanation of the demo before the exposure. They also could observe others interacting with the origami and had access to the sample origami. Due to the nature of the arrangement, we also kept the questions to a minimum, and since the participants' exposure time was short, we did not measure cybersickness.

The experiment consisted of three different material conditions (Soft, Medium, and Stiff). We counterbalanced the conditions using a Latin square. At the beginning of the experiment, users would be equipped with the HMD to see the VE. They could observe their virtual hands as well as the virtual wall. Once ready, they pressed a virtual Start button to proceed with the first condition. The virtual wall color was set according to the condition (green for Soft, purple for Medium, and blue for Stiff). Participants were instructed to push the virtual wall as long as they did not push further than the virtual capsule limit, representing the maximum displacement

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that could be done for the condition. Participants could push and release the virtual wall as long as they wanted. Once done, they could press the Next button, and then the UI appeared to answer the following Likert scale question: ”Pick one term that best describes your current experience.” Possible answers were displayed from left to right with the following labels: ”Very Stiff (1)”, ”Somewhat Stiff (2)”, ”Neither Stiff nor Soft (3)”, ”Somewhat Soft (4)” or ”Very soft (5)”. After answering the Likert questions, people were instructed, ”What material would you relate your experience with? Please, say aloud.” The experimenter entered the answer in the UI text field and then we proceeded to the next condition. Participants would repeat the same procedure for the two remaining conditions and will take off the HMD to end the experiment.

124 participants tested the setup. To allow many participants to test the setup regardless the user study, we did not ask participants to fill in a consent form and a demographics form. Should a participant not consent to have data recorded, we were launching the experience without data record. Due to technical difficulties, we removed 18 participants from the first day. We removed 30 participants who did not complete the experiment or did not provide answers to the conditions tested. This resulted in 76 participants who performed the entire experiment with the complete data provided.

5 Results

The gripper sensor data and the timestamps were recorded at 10 Hz. We computed the magnitude of the gripper data, represented as a 3D vector, and then resampled and normalized the temporal sequences so that we could compare the temporal sequence. On average, one trial lasted around 40 seconds. Fig. 6 shows a typical temporal sequence of magnitude for each material condition from one participant. This shows how the gripper's magnitude evolved across conditions during one given trial. A peak shows a participant's pressure on the origami to experience the stiffness of the material. We can notice similar pressure behavior across the three conditions.

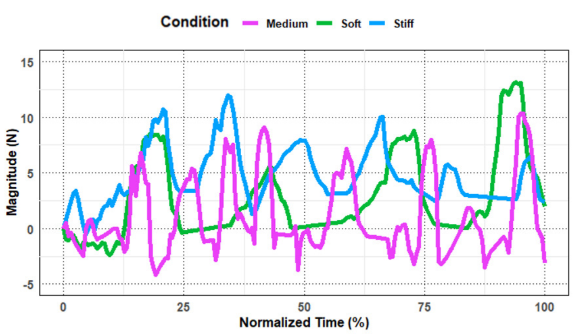

Figure 6: Typical temporal evolution of the magnitude of the gripper sensor data over time per condition (soft in green, medium in purple, and stiff in blue).

Fig. 7 shows the average answer of the perception Likert question asked after each condition, grouped by sequence order (i.e., the first condition, second, then the last). Likert answers regarding material perception were normally distributed. A Friedman rank sum test with Condition as a within-subject variable showed no statistically significant effect of the Condition on the Likert answers in general ($\chi^2(2) = 2.06$, $p = 0.35$), where average answers were similar across conditions: $M = 3.19$; $SD = 1.23$ for Soft, $M = 3.30$; $SD = 1.11$ for Medium and $M = 3.07$; $SD = 1.12$ for Stiff.

Regarding the material description as a free text answer, we sanitized the text data by putting the text in lowercase, switching plurals to singulars, removing stem words, and correcting typos that could have been entered during the experiment. Fig. 8 shows word-clouds for each condition. Overall, the top ten most recurrent

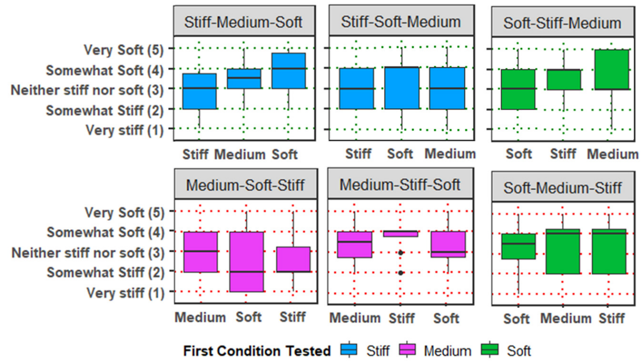

Figure 7: Box plot of the Likert stiffness perception question ”Pick one term that best describes your current experience.” grouped by condition (Soft, Medium, Stiff) and Sequence Order. The color indicated which condition was tested first

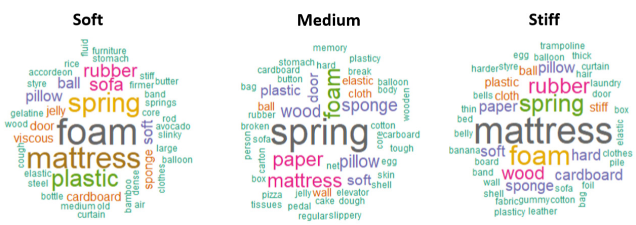

Figure 8: Wordclouds of answers to the question ”What material would you relate your experience with?” per condition (left for Soft, middle for Medium, and right for Stiff). The higher a word was mentioned, the bigger and more centered it is.

answers were: mattress (24), spring (22), foam (21), soft (12), plastic (11), pillow (10), rubber (10), wood (9), sponge (8), paper (8). In particular, we noticed that the highest occurrences found for each condition were: foam (10) for the Soft condition, spring (10) for the medium condition, and mattress (8) for the Stiff one.

6 Discussion

Our study focused on how origami-based end-effectors could provide different stiffness feedback. Our objective results found that correct stiffness perception was not always accurate based on the conditions tested, but the subjective results reported different material perceptions. The overall benefit of using the origami structure is in the immediacy of the dynamic feedback and the simplicity of control as opposed to devices like a robotic arm with a high degree of freedom. A robotic arm requires the motion to be planned and carefully executed in the right order by a number of actuators, which takes time and prevents fine interactions. Whereas the origami's state is controlled by only a single actuator while it provides immediacy through its inherent materiality. Another benefit of the origami is the ability to compress itself which is important for collision avoidance should it be employed in motion (e.g. mounted on rails or a robotic arm).

One of the study's limitations is its brevity of exposure, which is limited to a demonstration. The participants experienced each condition only once and in a non-controlled environment. This suggests that the calibration of the participants' expectations had to happen very fast. In Fig. 7, we can observe what might be an order effect on early calibration. The best and most accurate estimates were in sequences where the stiff material was first. Overall, the participants clearly differentiated between the stiff and soft materials, whereas the medium material with plastic-elastic deformation was

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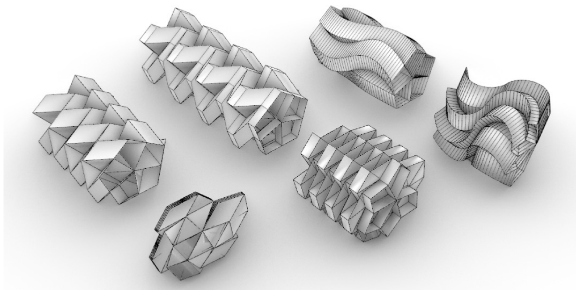

Figure 9: Zipper Flower Tubes design variations in expanded and collapsed states: (left) Flat-foldable zig-zag tube, (center) zig-up-zag-up tube with adjustable length, (right) semi-discrete flower with developable strips.

somewhat confusing, especially if introduced first. Future work should consider additional experiments in a controlled environment with different conditions and a higher number of repetitions.

We also observed the differences between the participants' focus during the experience. Some participants dynamically evaluated the stiffness as intended by the pressure required to achieve the maximum deformation. However, some participants were more fixated on how the final stage of the deformation felt on its own. They often underrated the light resistance and springiness of the relaxed (soft) origami and declared it to be "stiff" when it was fully collapsed. And vice versa, when a stiffer material was simulated, and the origami was contracted, providing more resistance from the beginning - this material was described as "soft" for its spring-like behavior. We theorize that this is a reason for the swapped results that might be somehow connected to the order effect discussed above. However, further investigation in a controlled environment must confirm this notion. As it can be seen in Fig. 6, participants were allowed to press as many times and as strongly as they desire, as long as they do not reach the pressure limit (which we indicated with visual feedback on the virtual wall turning red). This might also explain the intra-individual variability that we observed during our study.

An alternative explanation would be the deterioration of the origami from use and insufficient difference in the stiffness levels for the new users. Although we tried to match our parametrization to force levels the paper origami could withstand, some of the participants applied stronger forces than anticipated when they went immersed. The dichotomy of expectations and differences in the perceived stiffness is reflected in Fig. 8. We see a certain convergence per material, and some of the descriptions overlap there to a smaller degree. One reason could be that the flat cardboard at the end of the tube may have had an influence on the material perception. For future research, we plan to optimize the geometry (design, dimension, number of sections and pedals) of the Zipper Flower Tube for better fitting the task, and to use advanced manufacturing methods (e.g., 3D print with flexible material for the joints realized as compliant hinges) for its production. Even semi-discrete versions assembled by developable strips are of interest in this context (cf. Fig. 9). A more rigid origami will be more durable and facilitate more accurate force transfer to the F/T sensor which in turn will enable us to provide a more distinct haptic experience for various materials.

7 Conclusion

Enabling the perception of particular materials or shapes is a fundamental requirement in the context of immersive early-stage design. Through the integration of action-origami with minimal mechanical actuation, we developed a flexible and immediately responsive prop that can provide low-cost and energy-efficient haptic feedback. Being able to render different stiffness levels haptically in quick succession with a single prop is ideal for the user experience. In this paper, we presented a user study that aimed to assess the usability of the Zipper Flower Tube. Our results showed that the Zipper Flower Tube can render different types of stiffness with deformation, thus providing insight regarding the potential of origami as an end-effector. Future work should consider improving the Zipper Flower Tube design to improve its durability and haptic accuracy, as well as a more in-depth investigation of users' stiffness perception.

Acknowledgments

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