HapticPipette: Seamless Capture of Object Compliance in Mixed Reality

Arata Jingu
Saarland University, Saarland Informatics Campus
Saarbrücken, Germany
jingu@cs.uni-saarland.de

Jianhui Yan
University of Glasgow
Glasgow, United Kingdom
3177699Y@student.gla.ac.uk

Maja Fehlberg
INM – Leibniz Institute for New Materials
Saarbrücken, Germany
maja.fehlberg@leibniz-inm.de

Roland Bennewitz
INM – Leibniz Institute for New Materials
Saarbrücken, Germany
roland.bennewitz@leibniz-inm.de

Jürgen Steimle
Saarland University, Saarland Informatics Campus
Saarbrücken, Germany
steimle@cs.uni-saarland.de

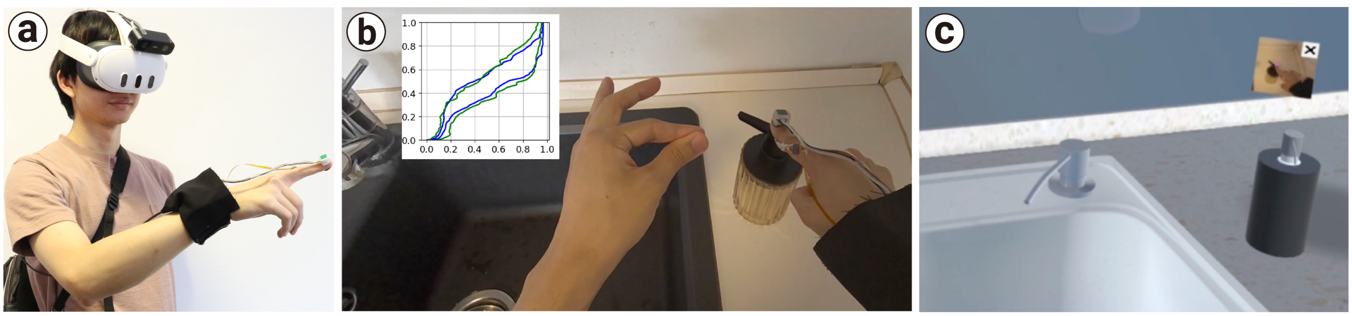

Figure 1: HapticPipette is a technique for seamlessly capturing the complex compliance response, a key factor of the perceived softness of real-world objects in MR environments. (a) Powered by an integrated setup and egocentric force-displacement measurement, (b) the user can easily capture the non-linear force-displacement response by touching the object. (c) This captured curve can then be applied to objects in MR to define their haptic behavior.

Abstract

Haptic feedback is essential in creating immersive mixed-reality (MR) experiences. Yet, specifying the haptic properties of virtual objects remains challenging, particularly when capturing the nuanced, non-linear force-displacement behavior that contributes to perceived softness. We present HapticPipette, a technique for seamlessly capturing the complex force-displacement characteristics of physical objects in real-time MR experiences. We contribute a mobile and finger-worn setup that allows users to capture the haptic characteristics with familiar finger movements while freely moving inside a room in MR experiences. Results from two user studies confirm that HapticPipette accurately captures force-displacement curves of diverse soft materials and that users find HapticPipette easy to learn and perform. Three example applications demonstrate how HapticPipette seamlessly integrates haptic capture into MR workflows.

This work is licensed under a Creative Commons Attribution 4.0 International License.
AHs 2026, Okinawa, Japan
© 2026 Copyright held by the owner/author(s).
ACM ISBN 979-8-4007-2351-3/26/03
https://doi.org/10.1145/3795011.3795022

CCS Concepts

• **Human-centered computing** → **Haptic devices**.

Keywords

Haptics; mixed reality; touch; haptic sensing; egocentric sensing; mobile.

ACM Reference Format:
Arata Jingu, Jianhui Yan, Maja Fehlberg, Roland Bennewitz, and Jürgen Steimle. 2026. HapticPipette: Seamless Capture of Object Compliance in Mixed Reality. In *The Augmented Humans International Conference 2026 (AHs 2026), March 16–19, 2026, Okinawa, Japan.* ACM, New York, NY, USA, 12 pages. https://doi.org/10.1145/3795011.3795022

1 Introduction

Softness is a pervasive quality in our everyday environment. We sit on soft cushions, sleep on soft bedding, grip soft handlebars, wear soft clothing, cuddle plush toys, and walk on soft grass. Even the human body itself is soft. Compliance is a critical factor in determining perceived softness [47], and is physically expressed as the force-displacement response, the relationship between the force applied to a surface and its resulting displacement [1, 16]. Objects exhibit a wide range of compliance profiles and thus substantially contribute to the realistic and distinctive haptic experiences [16, 37] that shape our physical interactions with the world. Our goal is to help bring this haptic richness into MR environments, where tactile feedback is becoming increasingly important. Specifically, we aim to enable designers to easily and rapidly integrate nuanced compliance responses into virtual objects.

However, designing an object's perceived compliance response remains a significant challenge. While compliance can be broadly categorized along a spectrum from soft to rigid, many objects exhibit complex tactile behaviors. For example, the perceived compliance may change non-linearly with applied pressure, sometimes even involving abrupt transitions. Additionally, hysteresis effects—where the sensation differs between pressing and releasing—are very common. This nuanced behavior makes it difficult to manually define an object's compliance profile from scratch. Direct capture and assignment of force-displacement responses offers a solution, yet existing methods often rely on linear approximations [14, 26], discarding distinctive non-linear and hysteresis behaviors. Furthermore, none of them present a mobile, finger-worn setup compatible with natural MR hand interaction. This requires switching between external tools and the conventional MR experience, impeding seamless haptic design—a bottleneck we aim to resolve.

To address this, we draw inspiration from two familiar paradigms: pipetting in the physical world and copy-and-paste interactions in graphical user interfaces. Both involve capturing a complex item through a simple gesture and reapplying it in a new context. Similarly, we aim for a method for easily capturing the nuanced compliance response of real-world objects for designing virtual haptic properties in MR environments.

We present HapticPipette, a mobile, finger-centric technique for seamlessly capturing the complex compliance response of physical objects for use in MR experiences (Figure 1). In this capture interaction, the user measures the compliance properties of a real-world object by touching it at any desired point. This action immediately generates a graphical element in the MR environment that represents the captured compliance response. It can be applied to a virtual or physical object in the scene to define its haptic characteristics, to be later rendered with any existing compliance rendering method (the latter is outside the scope of our contribution).

HapticPipette is based on three key technical contributions: First, we present a set of *interaction techniques* that allow users to seamlessly capture an object's force-displacement curve, integrated into existing MR workflows. Second, we contribute a *mobile and finger-worn setup* that supports all interactions directly through the user's finger, while supporting existing touch interactions with virtual and physical objects. It allows the user to freely move in a 3D space and start interactions with their familiar finger wherever they want, instead of using complex and tethered haptic tools. Third, we contribute *egocentric force-displacement measurement*, the first technique for capturing non-linear force-displacement curves of real-world objects in a fully wearable setup, by tactile exploration. It employs a finger-worn capacitive force sensor and a head-worn egocentric RGB-D camera. Leveraging visual-inertial odometry, it accurately tracks object displacement under applied force, despite inevitable body motion and unpredictable soft-object deformation.

Results of a user study revealed that (1) the proposed egocentric force-displacement measurement approach successfully captured the overall shape of the non-linear force-displacement curves of 11 different materials that exhibit strong non-linearity and elastic hysteresis, and (2) the proposed HapticPipette interaction has high usability. In three applications, we demonstrate how HapticPipette enables end-users and designers of MR environments to seamlessly capture the haptic characteristics of objects and surfaces in MR, including (1) designing the haptic response of virtual objects, (2) augmenting the haptic response of real-world objects, and (3) sharing haptic properties between remote users.

In summary, this paper makes the following contributions:

- The concept of HapticPipette, a technique that allows users to seamlessly capture the compliance characteristics of objects in real-time MR experiences, using simple and familiar finger movements.
- Egocentric force-displacement measurement to capture non-linear force-displacement curves of real-world objects in a wearable setup.
- Results from two user studies confirming HapticPipette can accurately capture force-displacement curves of soft objects with a highly usable interaction.
- Example applications demonstrating how HapticPipette can enhance MR experiences.

2 Related Work

Our work builds on the intersection of two areas: haptic design and force-displacement measurement.

2.1 Haptic Design and Capture for MR experiences

Designing haptic experiences is a very complex task as it requires extensive knowledge of hardware, software, and human perception [13, 30, 35]. To make haptic design easier, various haptic design tools have been proposed. They allow users to create a new haptic pattern from low-level parameters (e.g., amplitude, frequency, and spatiotemporal movement) [7, 10, 25, 32, 34, 43], provide support for editing existing haptic patterns [12, 31], allow designers to trigger a haptic pattern in response to a specific event [31], to build a library of haptic patterns [11], or to generate a vibration signal from a text description using emerging text-to-vibration models [39]. Despite this richness of features, in the task of designing haptic properties for virtual objects in MR experiences, the user has to first create or assign haptic patterns to virtual objects on these desktop GUI-based tools and then test them in an MR setup. This discrepancy between haptic design tools and MR experiences requires haptic designers to frequently switch between a desktop and an HMD during design iterations.

For rapid prototyping of haptic patterns, in-situ VR haptic design methods based on user-defined cues have been proposed. These allow for designing and testing haptic patterns directly in a VR scene. Degraen and Fruchard et al. [5] proposed designing temporal patterns for a hand-held haptic feedback device through the user's vocalization. Sung et al. [40] designed spatiotemporal haptic patterns for the whole hand based on the user's spatial input and the hand's posture. While these approaches enabled rapid haptic design, the users have to create haptic patterns from scratch based on the user's imagination of a virtual object, still making it difficult to design complex haptic characteristics that correspond to the properties of real-world objects.

Due to this difficulty, some research works have aimed to directly capture the haptic characteristics of a real-world object. This idea has been investigated for several haptic characteristics, such as surface textures [4, 6, 17, 26, 41], linear force-displacement response [14, 26], friction [4], tapping [4], and vibration [24]. None of them have presented a mobile and finger-worn device setup to enable end-users to achieve capture haptic responses in a single MR environment, which impedes a seamless haptic design in MR experiences. To address this issue, we offer an integrated MR environment and a capture interaction technique to seamlessly conduct haptic capture from real-world objects with a finger-worn haptic interface compatible with existing finger gestures used in commercial head-mounted displays.

2.2 Approaches to Force-Displacement Measurement

A force-displacement curve is the relationship of the surface's displacement to the force applied to the surface. It is one of the fundamental haptic characteristics of an object and one of the primary factors of softness sensation, aside from tactile cues [47].

A real-world object has a characteristic non-linear force-displacement curve that depends on its haptic characteristics, such as linear, convex, concave, or a mixture of multiple functions [2, 15, 16]. These various non-linear force-displacement curves provide realistic and distinctive compliance characteristics of virtual surfaces [16, 37]. Notably, the shape of the curve can be different for pressing and releasing cycles due to hysteresis. These unique and non-linear behaviors make it difficult for the user to design a force-displacement response from scratch, leading to a demand for directly measuring a force-displacement response from a real-world object.

Traditionally, the force-displacement measurement has been conducted with a grounded setup comprising a force sensor and a probe that records the applied force and resulting displacement when an object is compressed, utilizing setups such as robotic arms [18, 26, 29, 33], motorized linear stages [1, 2, 28], or custom-built benchtop apparatus [3, 21]. While these setups enable the precise measurement of a force-displacement curve, their grounded and bulky form factors prevent mobile use. To enhance mobility, some researchers have proposed a handheld setup for measuring the object's stiffness [36, 38]. However, they only measured the linearly approximated force-displacement response and were still tethered to an external grounded computer. Vision-based tactile sensors, such as GelSight [48], capture high-resolution surface geometry and estimate contact forces via the deformation of an internal elastomer. However, these sensors are inherently limited to measuring microscopic surface deformation and cannot track the global surface displacement required to measure the macroscopic force-displacement behavior of soft objects.

Extending upon this body of prior work, we contribute the first system to conduct the non-linear force-displacement measurement with a fully wearable setup.

3 The HapticPipette Interaction

HapticPipette allows the user to capture compliance characteristics of real-world objects with interactions that are seamlessly integrated in the MR experience. We have designed these interactions and the corresponding interactive system with three key goals:

Integrated MR Environment for Haptic Capture. HapticPipette seamlessly integrates haptic capture of real-world objects in an integrated and consistent MR experience. It frees users from switching between devices and interfaces, as required in existing approaches that separate haptic capture of real-world objects from MR design.

Mobile and Finger-Worn Interface. HapticPipette offers a mobile and finger-worn setup that achieves the capture interaction while naturally supporting existing finger-based interactions with virtual and physical objects. We implemented these interactions with a finger-worn capacitive force sensor (SingleTact), a head-worn RGB-D camera (Stereolabs ZED), and an MR head-mounted display (Meta Quest 3, applications built with Unity), all commercially available. The mobile setup allows the user to move freely inside a room or across rooms, and to interact with any object or surface in the environment. This frees the user from restrictions associated with common immobile or tethered setups for haptic capture, such as benchtop measurement devices for capturing force-displacement curves [1].

Finger-Based Interaction. HapticPipette enables users to interact with both physical and virtual objects using their familiar fingers as a unified medium. Through natural exploration of an object's surface, users can intuitively measure its haptic properties. At the same time, they can directly manipulate virtual objects using standard MR finger gestures.

In the capture interaction, the user performs a physical interaction to measure the force-displacement response of a real-world object or surface (see Figure 2a-1). The user first activates the capture interaction by pinching with the non-dominant hand (a-2). While keeping this pinch gesture, the user conducts the capture by slowly pressing and releasing a target real-world object with the index finger of the dominant hand (a-3). This can be done once, or successively multiple times. The system automatically keeps recording a time-synchronized series of force values from the finger-worn force sensor and corresponding displacement values from the head-worn RGB-D camera, which capture the extent to which the object is indented under the applied force. The capture is finished by ending the pinch gesture (a-4). The raw recorded data is immediately converted to a force-displacement curve and is visualized as a new haptic material in the MR environment. The captured haptic materials are saved in the library and are always accessible to the user. At the start of any recording, the camera additionally retrieves a cropped RGB image of the target object, which serves as a visual icon representing the haptic material in the library.

As a supplementary interaction, the user can assign a haptic material to a virtual object in the MR environment. The user drags a haptic material appearing after the capture or from the library (Figure 2b-1) and drops it on a virtual object or a defined area on a physical object in the MR environment (b-2, b-3). Expert users can further expand the icon, inspect the force-displacement curve, and fine-tune the curve by scaling the curve shape on the displacement axis with the slider (b-4).

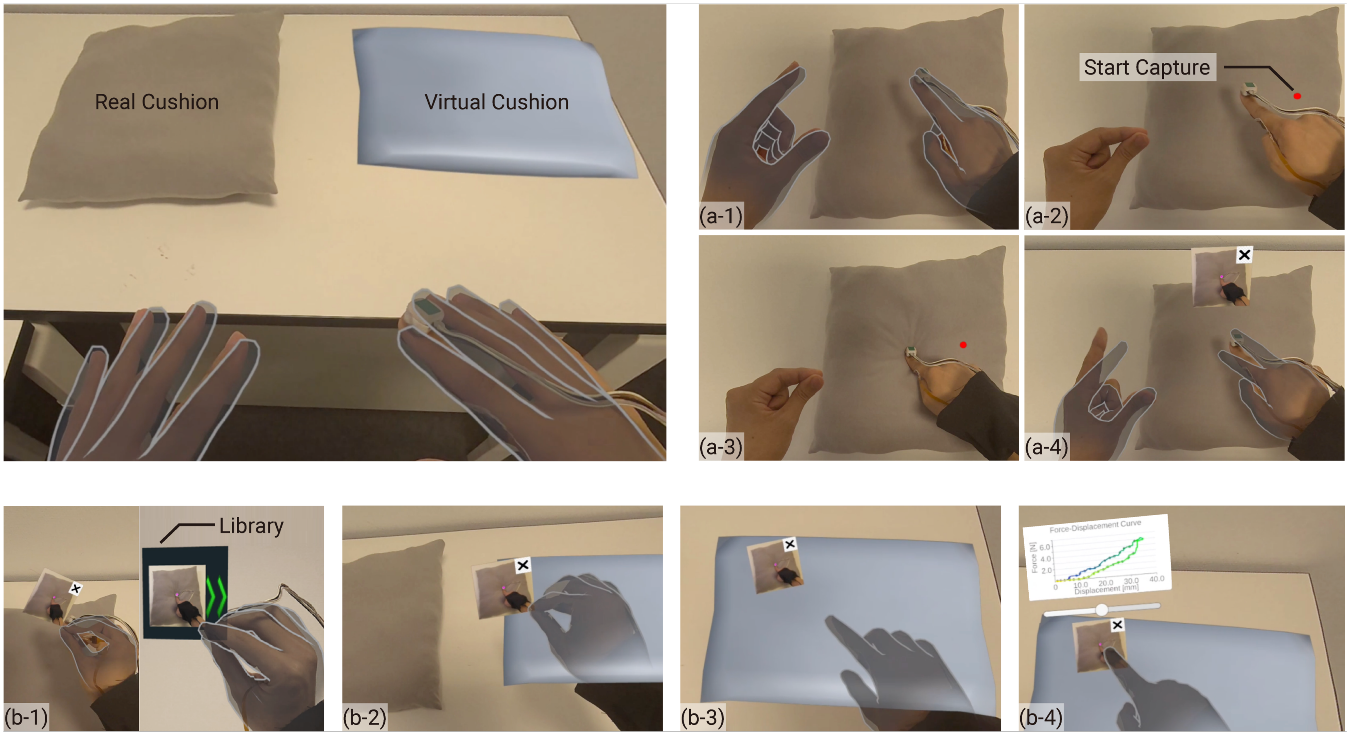

Figure 2: (a) HapticPipette allows the user to seamlessly capture objects' force-displacement curves by pinching to start capture mode while pressing into the object. (b) Each captured profile is immediately visualized in the MR environment and can be applied to virtual and physical objects using drag-and-drop.

4 Egocentric Force-Displacement Measurement

To technically enable the HapticPipette interaction technique, we contribute an approach for egocentric force-displacement measurement with a mobile and finger-worn setup. It enables end-users to measure the compliance properties of real-world objects or surfaces. It captures an object's non-linear force-displacement curve by measuring the applied force with a finger-worn force sensor and tracking the finger displacement with an egocentric RGB-D camera. Figure 3 illustrates the system setup. Solely for use in application demonstrations, we put a fingernail-mounted device in Figure 3 that renders compliance based on vibrotactile grains [44] in a mobile form factor.

Egocentric vision [8, 22] is a growing research area of computer vision that captures the user's activities or the surrounding environment with a wearable first-person camera. Compared to traditional third-person sensing, it especially has merits in capturing the user's daily activities involving object manipulation [8]: the user can freely move in a 3D space and interact with objects on the spot, without the need for instrumenting the environment. Furthermore, the egocentric perspective can be beneficial in minimizing occlusions of manipulated objects in the camera view. Similarly, this egocentric vision approach has a high potential for mobile interaction. Using our system, users can freely move in the environment and capture force-displacement curves on the spot, solving the mobility issue of conventional force-displacement measurement approaches that typically use grounded setups [2].

Egocentric force-displacement measurement entails two technical challenges that were not seen in conventional force-displacement measurement approaches: (1) accurate measurement of finger displacement during contact with a soft object, robust to deformation of the non-rigid surface and to head movement, and (2) accurate measurement of the force the finger exerts onto the object, in a way that does not impede the user's touch exploration. For accurate reconstruction of a force-displacement curve during natural touch interactions, both measurements must have a high framerate. We now present how we have addressed these challenges.

4.1 Capturing Finger Displacement

Achieving precise tracking of finger displacement on soft objects with RGB-D data requires addressing multiple technical hurdles. First, pressing on a non-rigid surface makes it demanding to continuously and accurately track the finger's position. As the finger moves into the possibly strongly deforming material, its contour can become indistinguishable from the surrounding surface in depth data [9], and the material of the surrounding surface can partially occlude the finger. Second, as the finger presses, the object surface surrounding the finger is deforming in difficult-to-predict ways; this prevents us from estimating finger displacement simply by comparing with reference measurements at locations surrounding the finger. Therefore, we opted for measuring finger displacement relative to the camera's position. This, however, brings about a third challenge: as the camera is mounted on the user's forehead,

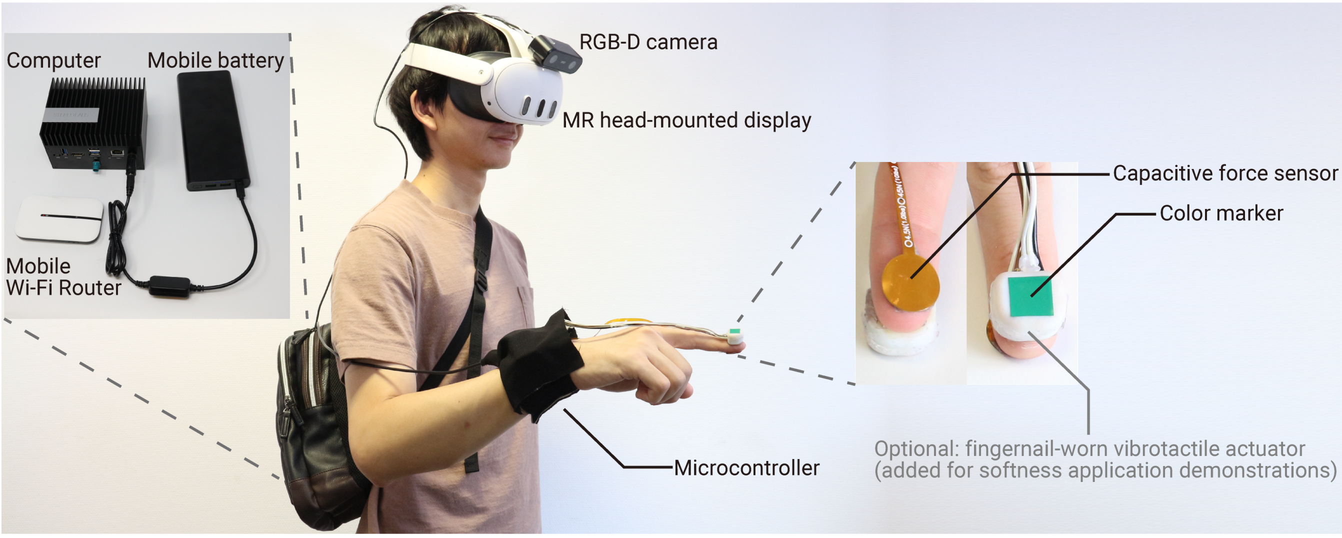

Figure 3: Egocentric force-displacement measurement allows the user to obtain a non-linear force-displacement curve of a real-world object with a fully mobile setup. (The vibrotactile actuator is not part of the technique itself; it was added as one example solution for compliance rendering in our application demonstrations.)

its position constantly changes in response to the movement of the user's head and body.

To address these issues, we use visual-inertial odometry (VIO) [19] to continually track the camera's movement with 6 degrees of freedom (position and orientation in 3D). VIO achieves robust and accurate localization by combining the detailed visual features of the environment captured by the camera with the accurate information about orientation and acceleration captured by an inertial measurement unit [19].

To robustly identify and track the finger's location in the depth image, even when pressed into a very soft surface, we attach a visual marker (green tape) to the index finger, at the upper side of the distal interphalangeal (DIP) joint. The 2D image coordinate of the tracked finger is first converted to the 3D camera coordinate in a real-world unit with the camera as the origin, using RGB-D information. Then, using the VIO result, the 3D camera coordinate is converted to the 3D world coordinate with the camera's 3D position where VIO started as the origin. This marker is visible in the camera's RGB image and allows for identifying the corresponding location in the depth image. We chose green as a relatively rare color for objects that people handle daily.

We implemented this approach using a commercial high-framerate RGB-D camera (Stereolabs ZED X mini). The camera is fixed on the user's forehead, on top of a head-mounted MR display (Meta Quest 3), attached via a hook-and-loop fastener. The camera captures RGB-D images in 960 × 600 pixels at 60 fps. It features a built-in implementation of visual-inertial odometry (VIO) that tracks the camera's pose with respect to the environment in 6 DoF at 51 Hz. It sends this data to the control unit via a GMSL2 cable. We use a commercial single-board computer (NVIDIA Jetson Orin NX 8GB) as a control unit. It is powered by a mobile battery (26800 mAh).

A mobile Wi-Fi router allows the control unit to communicate via Open Sound Control (OSC) with a Unity application that runs in the HMD. Jetson, Wi-Fi router, and the battery are carried in a shoulder bag.

Our evaluation results, presented below, show that the presented approach allows us to capture finger displacement on soft objects with a mean absolute error of 1.46 − 3.39 mm.

4.2 Capturing Force

Our technique requires a force measurement method that balances accuracy with a finger-worn form factor. For instance, a portable load cell has high accuracy but blocks the user's finger from exploring objects through touch. In contrast, some finger-worn force sensing approaches, e.g., force-sensitive resistors (FSR) or visual force sensing based on visible nail color [45] or photo-plethysmography (PPG) [23] offer ergonomic form factors with high mobility but not enough repeatability and accuracy in Newton units. To solve this, we adopted a capacitive force sensor. Its thin, lightweight, slightly deformable form factor allows the user to fix it on the curved finger surface and to record the force value without blocking the user's natural object manipulation. It has high repeatability and accuracy, which makes it the most suitable option among other approaches. We chose a commercial capacitive force sensor (SingleTact[1]) that has a 15 mm diameter and is 0.30 mm thick. It captures 0-45 N divided into 512 steps (typical repeatability error < 1.0 %, linear error < 2.0 %, hysteresis < 4.0 %, response time < 1 ms, according to the datasheet). This sensor is connected to the wrist-worn microcontroller (Teensy 4.1), which sends the force values to the control unit at 63 Hz via a USB cable.

5 Evaluation

To validate HapticPipette, we conducted two studies that investigated (1) the proposed egocentric force-displacement measurement

[1]https://www.singletact.com/

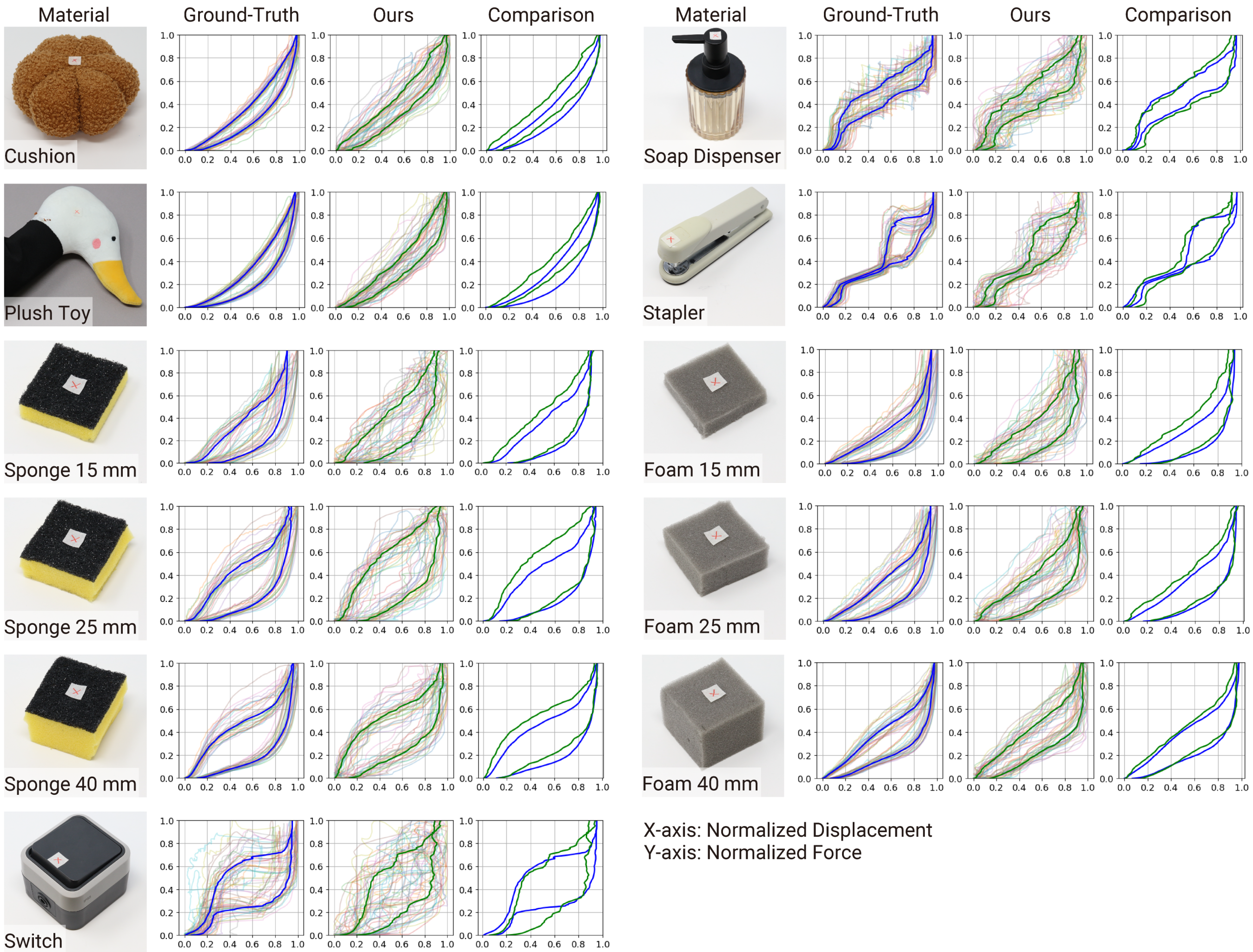

Figure 4: Force-displacement curves captured with our proposed method and a benchtop ground-truth capturing setup for all 11 materials. Leftmost and center graphs: force-displacement curves of all participants normalized by each participant's maximum force/displacement values (light gray) and their median curve (color). Rightmost graph: median curves of both methods overlaid. The results show that our method captures the overall shape of the ground-truth material response, including strong non-linearity and strong hysteresis.

and (2) the usability of the HapticPipette interaction. Both studies were approved by the Ethical Review Board of our university.

5.1 Study 1: Technical Evaluation of Egocentric Force-Displacement Measurement

This study aims to demonstrate that the proposed method can measure force-displacement curves with high accuracy for various soft materials.

Material Conditions. We selected 11 everyday materials to cover a broad spectrum of force-displacement curve responses (e.g., stiffness, hysteresis, and step-changes), representative of many soft objects in our daily environment. The materials are shown in Figure 4: cushion (70 mm thick), plush toy (60 mm thick), double-layer sponge (15, 25, and 40 mm thick), foam (15, 25, and 40 mm thick), momentary rocker switch (7 mm pushable distance), soap dispenser (15 mm pushable distance), and stapler (17 mm pushable distance). We purposefully added particularly challenging materials (such as switch, soap dispenser and very soft materials) to identify the boundary conditions of our method.

Apparatus. We simultaneously measured force-displacement curves with both our proposed method and a high-accuracy ground-truth measurement method. The ground-truth method combined an industry-grade grounded 3-axis force sensor (ME-Messsysteme K3D120, 0-50N) and a high-framerate optical tracking device (OptiTrack V120:Trio). While the ground-truth method needs a grounded setup, on a desk, it can be considered a highly accurate approach and works with our method simultaneously. The grounded force sensor is fixed to the desk 820 mm below the optical tracking device. The ground-truth method captures the time-synchronized data of the applied 3-axis force and the 3D position of a retroreflective marker at 120 fps. We only used the force and position in the downward-facing direction for both methods to align the coordinate axes. To ensure consistency between the two different force sensors, the experimenter conducted the sensor calibration in advance by collecting data when directly pressing the grounded force sensor with their finger, with the wearable force sensor on it. During the measurement, the participant sat in front of the desk, with our system's RGB-D camera fixed to the head and the capacitive force sensor attached to the index fingerpad with double-sided adhesive. A piece of green tape was put on the entire DIP joint. In addition, a retroreflective marker, needed for ground-truth optical tracking, was affixed at the center of the green tape. We recorded ground-truth force and displacement data, the data from the finger-worn force sensor, as well as the position tracking data from the head-worn RGB-D camera.

Study Procedure. After the experimenter had explained the study, the participant filled out the consent form. Before the actual measurement session, the participant conducted one training trial. At the start of each measurement, the participant double-tapped the material quickly as a temporal synchronization cue between the two setups for later data analysis. A visual indicator on the material indicated the point where the participant should touch. Then, while looking at the material, the participant pressed the material surface downward until the finger could not press further, and then released it. This was done 3 times consecutively. In-between trials, the finger was positioned slightly above the material surface. We instructed participants to press and release the material in a way they consider natural, at a moderate speed. Participants were also instructed to keep their head and body as steady as possible during each measurement and avoid any skin area other than the wearable force sensor from contacting the material. Each participant conducted the above procedure for all 11 materials in a randomized order.

Participants. We recruited 10 participants (aged 23 to 44; 5 identified as male, 5 as female; all right-handed). Each study session took approximately 30 minutes.

Analysis Method and Results. We processed the raw time-series of force and position data into a format that allows for a comparison between our proposed method and the ground-truth method. First, the raw values of the wearable force sensor are converted to force values in N units based on the sensor calibration result. The force and displacement data were smoothed using a Savitzky–Golay filter with a cubic polynomial and a 7-window size. We aligned the time-series force and position data of the proposed and ground-truth methods using the recorded synchronization cues and cropped them for the 3 trials of press/release by thresholding based on the values of the grounded force sensor. We calculated the relative displacement data in each trial by subtracting the distance recorded at the first data frame of the trial. We separated each force-displacement curve into press/release curves at the data point where the sum of normalized force and displacement values was the largest. We calculated the mean absolute error (MAE) between the time-synchronized time-series data of the ground-truth and our methods in terms of displacement and force, both for absolute values and values that were normalized for each experimental condition and participant. While the perceived realism of final haptic feedback also depends on the rendering hardware, a low MAE ensures that the force-displacement behavior of a real-world object is correctly digitized, which contributes to reproducing more realistic perceived compliance in MR haptic experiences. We then calculated force-displacement curves for both our proposed and the ground-truth capture method, using normalized force and displacement data. We calculated the median curves of all press/release curves for each material and smoothed these curves using a Savitzky–Golay filter with a cubic polynomial and a 7-window size.

Material	Displacement [mm]	Normalized Displacement	Force [N]	Normalized Force
Cushion	3.39	0.043	3.71	0.070
Plush Toy	2.75	0.039	3.19	0.087
Sponge 15 mm	1.46	0.071	2.22	0.051
Sponge 25 mm	1.74	0.071	2.87	0.059
Sponge 40 mm	1.91	0.046	3.26	0.064
Foam 15 mm	1.63	0.065	1.66	0.043
Foam 25 mm	2.37	0.060	2.38	0.053
Foam 40 mm	3.08	0.056	3.10	0.050
Switch	2.09	0.138	0.49	0.049
Soap Dispenser	1.93	0.075	1.88	0.053
Stapler	2.04	0.087	1.31	0.033

Table 1: Mean absolute errors (MAEs) for displacement and force measurements between the time-series data of the ground-truth and our capturing method. It shows MAEs for the raw data and the data normalized by each participant's maximum force/displacement values.

Table 1 shows the MAE metrics for each material, denoting the error between the measurements captured with our method and the ground-truth method. Figure 4 shows the force-displacement curves for the ground-truth and our proposed method for each material. For each material, the left and center graphs include force-displacement curves of all participants normalized by each participant's maximum force/displacement values (light gray) and their median curves (color). For better direct comparison, the right graph includes the median curves of both the ground-truth and our methods. For each force-displacement curve, the upper curve is for pressing and the lower one for releasing.

Discussion. We note that the force-displacement curves recorded with our wearable setup accurately capture the overall shape of the ground-truth material response. This comprises non-linear responses that are convex, concave, or highly irregular, up to sudden step-changes exhibited by the stapler. As the plots reveal, our proposed method is also capable of capturing the pronounced hysteresis behavior of soft materials, indicated by the different shapes of the force-displacement curve when pressing in vs. releasing the finger. Moreover, these diverse shapes of non-linear force-displacement curves firmly indicate the importance of non-linear force-displacement measurements, not only linear ones. We consider the captured accuracy acceptable for our target application of MR interaction design. In this context, the primary criterion is not industrial-grade precision, but rather the preservation of the distinctive shape and hysteresis of the profile, which defines the object's overall compliance characteristics. Notably, the switch was most demanding for accurate force-displacement measurement due to its short pushable distance and quick step-change movement.

Displacement MAE was moderate for most materials with values between 1.46 mm and 2.37 mm. Slightly larger displacement MAE of up to 3.39 mm was seen in strongly deformable materials (cushion, plush toy, and foam). This could be because the green marker on the finger became partly covered by the strongly deformed surface, interfering with the correct position tracking from the RGB-D camera. We hypothesize that this issue could be improved with a more sophisticated finger-tracking algorithm.

Larger force MAE was seen in strongly deformable objects (cushion, plush toy, sponge 40mm, and foam 40 mm), where our proposed method always reported smaller force values than the ground-truth method. A plausible explanation could be the known behavior of thin-film force sensors that tend to report slightly lower values when pressed onto soft objects, due to an uneven pressure distribution on the non-planar contact surface between the finger and the material [42]. This assumption is supported by the comparatively smaller force MAEs measured for materials with a planar, non-deforming surface (switch, soap dispenser, stapler). One possible solution is to develop an advanced calibration method between the two force sensors that takes into account the deformability of the material surface surrounding the pressing finger. Also, the force errors seem large for daily pressing interaction, probably because the participants tried to press harder than usual to make sure further displacement did not happen.

We observed that the force-displacement curve of the three trials slightly differed even for the same participant and the same material, and this was visible even in the ground-truth method. This could be attributed to the quick measurement with uncontrolled conditions, where the participant was free to choose the maximum force and speed of indentation. We also instructed the participants to press the surface at an angle so that the wearable force sensor was roughly horizontal to the grounded force sensor. This differs from conventional force-displacement measurement protocols that are typically conducted with a rigid indenter of defined shape, at a carefully controlled angle, velocity, and force. It is informative to observe that despite the natural variations in our study, which are representative of real-world interactions, the overall shape of the force-displacement curve could be reconstructed. We conclude that in casual MR applications, such as the ones presented below, one single measurement may be sufficient; however, the reconstruction accuracy can be further increased by probing the material several times consecutively and calculating the average curve.

5.2 Study 2: Empirical Evaluation of HapticPipette Interaction

This study aims to demonstrate the usability of the HapticPipette interaction: capturing the force-displacement curves of the physical materials in the MR experience. The participants also experienced the supplementary interaction of applying the captured haptic data to virtual objects placed in the MR environment using drag-and-drop.

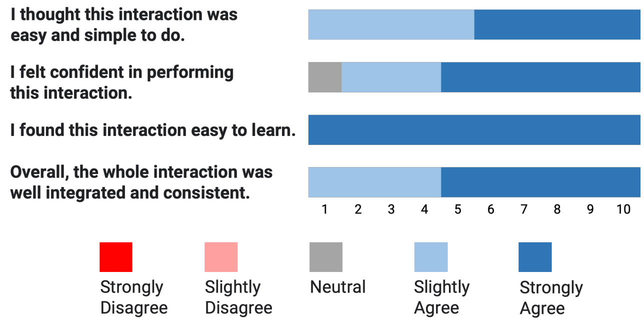

Figure 5: Study 2 revealed that HapticPipette interaction was easy to perform, easy to learn, and well integrated.

Participants. We recruited 10 participants (aged 23 to 44; 6 identified as male, 4 as female; all right-handed). Each study session took approximately 30 minutes.

Apparatus. The participant wore the setup shown in Figure 3 without a haptic rendering device in this study. To ensure the experimenter could check the experimental status, the MR HMD was connected to the experimenter's computer via a USB cable. Jetson was placed on a nearby desk and connected to the monitor, keyboard, and mouse so the experimenter could observe the experimental status. The participant stood in front of the desk where the materials for the capture were placed. We chose four representative materials (Cushion, Foam 40 mm, Stapler, and Soap Dispenser) from Study 1 to evaluate usability across primary compliance categories, ranging from large soft deformation to mechanical actuation.

Study Procedure. After the experimenter had explained the study, the participant filled out the consent form. After wearing the devices, the participant experienced the capture interaction under the experimenter's instructions. After these steps, the participant was allowed to conduct this interaction freely. After the experience, the participant completed a questionnaire. As an exploratory usability evaluation following recent AR authoring research [27], we adapted the questionnaire from the System Usability Scale [20] and focused on the usability of the capture interaction itself rather than a comparative baseline, selecting specific items to target: the ease, confidence, learnability of interaction, and how well participants perceived the interactions to be integrated. The session concluded a semi-structured interview that covered the participant's experience, potential applications, limitations, and need for improvement. The interview was audio-recorded for later analysis.

Results and Discussion. Figure 5 shows the participants' subjective responses. The capture interaction was rated as easy and simple to perform (AVG = 4.50, SD = 0.53), making participants confident in their performance (AVG = 4.50, SD = 0.71), and easy to learn (AVG = 5.00, SD = 0.00). Furthermore, the whole HapticPipette interaction was found to be well-integrated and consistent (AVG = 4.6, SD = 0.52). These results indicate the proposed interaction is highly usable when the users capture haptic properties directly in MR experiences.

In the interviews, participants referred to the capture interaction as *"intuitive"* (P1, P2, P3, P4, P5, P7), *"easy to learn"* (P5, P6), *"quite easy enough to perform even for beginners"* (P10), *"quite easy to capture. (...) recording with just one finger (...) was nice"* (P3), and *"[there are no] other external sensors or anything to use, and all we have to do is just use our hands. (...) so it was quite smooth"* (P10). All participants responded that the entire HapticPipette interaction was well-integrated and consistent and characterized them as *"fluid"* (P5) and *"smooth to switch from one task to the other"* (P6).

We found two main areas for improvement. First, it was sometimes seen that the left hand unintentionally pinched and activated a new capture: *"while I'm not thinking of stuff [= Capture interaction] and I start new captures"* (P7). Second, some participants suggested refining the visualizations of haptic data: *"some other way to visualize the haptic curve [= force-displacement curve] would be more helpful if it's somebody who's not very familiar with haptics"* (P3).

The participants saw the real-world relevance of the concept. They proposed application cases mainly for designing haptic responses for immersive experiences and for remotely sharing haptic data: *"for VR designers that want to design immersive gaming experiences (...) I'm pretty convinced they could, with that system, also quite easily customize their environment"* (P6), *"transfer [haptic data] remotely to another person's VR environment"* (P4). These ideas solidified our application cases in the next section.

6 Applications

This section demonstrates how HapticPipette opens up new MR experiences by seamlessly integrating capture interactions. Our applications focus on real-world objects with strong non-linear force-displacement curves, which is enabled with our wearable form factor.

6.1 Designing the Haptic Response of Virtual Objects

Conventionally, haptic design for a virtual reality (VR) scene is time-consuming, requiring designers to switch between separate tools for measurement, editing, and rendering. In contrast, HapticPipette allows VR designers to seamlessly capture the force-displacement responses of physical objects, directly in the MR environment, apply them in the virtual environment, and feel haptic experiences. Figure 6 depicts a designer designing a VR kitchen scene. (a) The designer captures the force-displacement response of a real sponge in an MR environment. (b) The designer switches from the MR to VR environment, applies the captured response to a virtual sponge, and experiences the feeling. As a representative technique for compliance rendering, we included a grain-based vibrotactile method [44] for our example applications. This approach employs a vibrotactile actuator (Vybronics VLV101040A) that is mounted on the fingernail and therefore can render compliance in a compact, wearable form factor. Note that our contribution focuses on capturing, and the method is compatible with any compliance rendering technique.

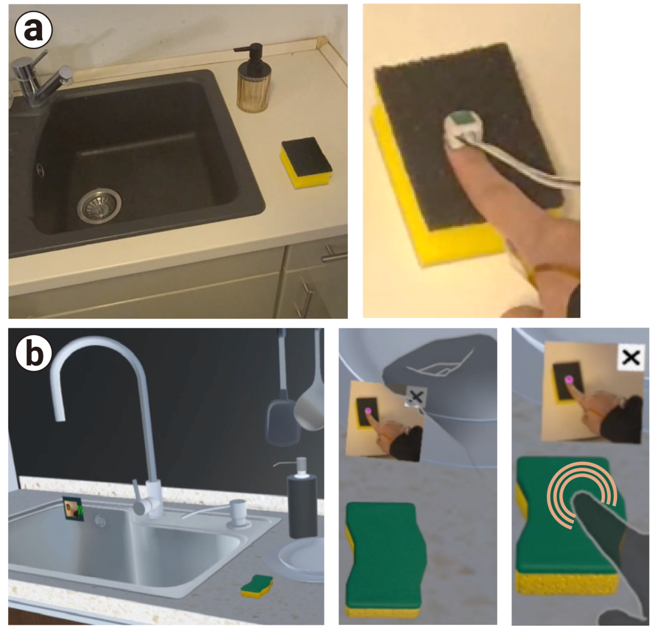

Figure 6: HapticPipette allows VR designers to seamlessly capture the force-displacement response of a real object and apply it to a virtual object: The designer (a) captures the force-displacement response of a physical sponge in an MR environment, (b) applies the captured response to a virtual sponge and experiences the feeling.

6.2 Augmenting the Haptic Response of Real-World Objects

In addition to designing haptics for virtual objects, HapticPipette can be used to augment the haptic response of a real-world object, which is present in the MR environment. For instance, an object can be modified to feel softer than it actually is. Figure 7 depicts a user *haptically augmenting* a physical birthday gift card for their child. (a) A 3D mesh area is placed on the gift card, which shall be augmented to feel softer. (b) The user captures the force-displacement curve from a plush toy and (c) applies it to the animal picture. (d) When touching the paper card, the system renders the assigned force-displacement curve and creates the sensation of a softer surface.

6.3 Sharing Haptic Properties between Remote Users

Today's applications for remote communication offer powerful audio-visual links; however, it remains difficult for users to share with remote people how an object feels. HapticPipette offers a new method for remote users to capture their local haptic experiences. Figure 8 depicts a user sharing the sofa they bought recently and their touch sensations. (a) The user captures the compliance of their sofa and (b) applies it to a 3D reconstructed mesh in a collaborative VR environment so that remote users can experience its visual and touch sensations.

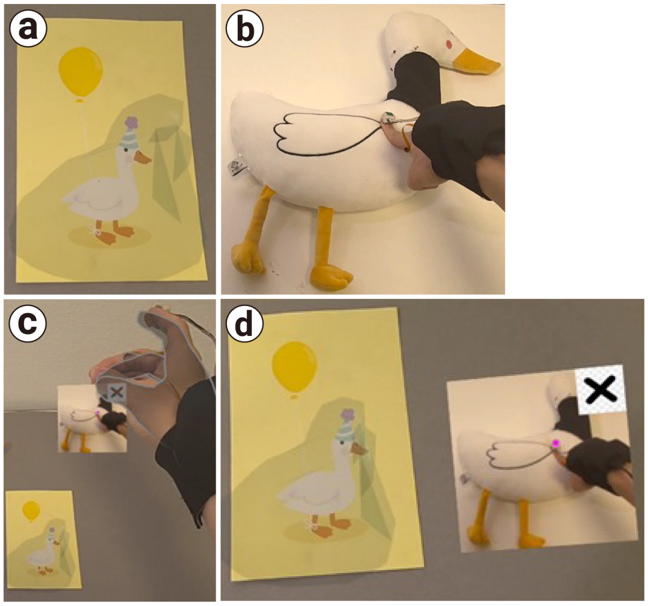

Figure 7: HapticPipette allows for haptic transfer between physical objects. (a) A physical gift card is seen through the MR headset, containing a picture of an animal. (b) The user captures the characteristic compliance response from a plush toy and (c) applies it to the picture. (d) The actuator renders a soft sensation when the user touches the paper card.

Figure 8: HapticPipette enables remote users to share their haptic experiences. The user (a) captures the compliance of their sofa and (b) applies it to a 3D reconstructed mesh in a collaborative VR environment, which other users can interact with.

7 Limitations and Future Work

While slight head movement is corrected for in our egocentric force-displacement measurement, the user is still advised to keep their head as steady as possible for accurate measurement. Future work should investigate even more robust 6 DoF camera tracking algorithms that perform accurately even under intense head and body movement. Regarding the camera specifications, although the current setup (60 fps) sufficiently captured the soft materials in Study 1, it may be less suitable for extremely rapid indentations or stiff objects with microscopic displacements. Future iterations could incorporate high-speed, high-resolution depth sensing to accurately track minute and rapid surface deformations.

In the time-series data of our study, we observed that one trial of press/release is usually done within 5 seconds, hence capturing can be performed rapidly. While the capture method was easy to learn, some participants would have preferred touching some of the materials with more than one finger. Notably, the stapler and soap dispenser are usually pressed with multiple fingers or the palm. In contrast, our current setup only supports single-finger interactions for capture. Future work should investigate techniques to cover interactions that involve grasping with multiple fingers, the entire hand, or even multiple hands. While users were free to choose the exact timing of how they touched the objects, participants were asked to press/release the material at a moderate speed. For some materials, this was a bit slower than when they naturally interacted with the material; of note, this applied to the switch, which is usually pressed rapidly and touched only for a very short time. To ensure fully naturalistic touch exploration even for these objects, the processing speed should be further increased in future work.

Due to the color-based sensing, the green marker has to be always visible to the camera during the measurement. This can be demanding when the finger pushes a quite soft object like foam because the fingertip can become partly occluded by the deformed surface. The marker can also be occluded from the camera depending on the finger angle, so the user is advised not to hide the DIP joint from the camera. In addition, similar to other color-based tracking work, our measurement approach is affected by other green objects in the scene or a poorly lit environment.

Our user study has investigated 11 materials with a variety of different, non-linear responses, including materials that exhibit strong hysteresis. However, all materials were planar, and we only considered a limited range of thickness. Future work should investigate this method in more diverse conditions in terms of material, size, shape, curvature, and thickness. Moreover, our current approach applies single-point measurement data uniformly to the virtual object, treating it as homogeneously compliant. Future work could explore systematic multi-point sampling to map spatially varying compliance across the entire object.

Our user study did not investigate fully controlled angle, velocity, and force conditions. Future work should investigate how their different conditions affect the measurement results.

The relatively small sample size in our user studies ($N = 10$ for each) could limit the generalizability of the results. Additionally, our use of a subset of SUS items might limit direct comparison with standardized usability benchmarks. Moreover, our current evaluation relied on subjective feedback. Future work should incorporate objective measures, such as task completion time and learning effects, with larger, more diverse participant groups and comparative evaluations to further validate the system's robustness.

As the first step of HapticPipette, we focused on only the force-displacement response among various haptic characteristics. Future work could extend HapticPipette to other various haptic modalities, such as surface textures, transient vibrations upon impact, and passive vibration. While our setup is already mobile and portable, further minimization of the prototype could be done in the future, such as ultra-thin interfaces for improved finger perception [46] and wireless communication between devices.

8 Conclusion

We have presented HapticPipette, a finger-based technique for seamlessly capturing objects' non-linear force-displacement profiles, integrated in real-time MR experiences with a fully mobile setup. The user can assign the captured haptic data to a virtual or real-world object to set its haptic response in an MR environment.

HapticPipette is based on three technical contributions: (1) a finger-based interaction that allows users to seamlessly capture haptic responses in MR environments, (2) a mobile and wearable setup that allows the user to freely move in a 3D space and start interactions with their familiar finger wherever they want, and (3) egocentric force-displacement measurement, the first technique for capturing non-linear force-displacement curves of real-world objects by a finger-worn capacitive force sensor and a head-worn egocentric RGB-D camera.

Results of the user study revealed that (1) the proposed egocentric force-displacement measurement approach could capture the force-displacement curves of 11 different materials with high accuracy, and (2) the proposed HapticPipette interactions are highly usable. In three applications, we demonstrate how HapticPipette enables MR end-users and designers to (1) design the haptic response of virtual objects, (2) augment the haptic response of real-world objects, and (3) share haptic properties between remote users.

Future work should investigate more detailed interactions of HapticPipette and more robust egocentric force-displacement measurement algorithms to further enhance the user's haptic experience. With HapticPipette, we aim to contribute toward a future in which end-users can quickly and easily customize their touch sensations, to make their MR environments more immersive, more functional, and more enjoyable.

Acknowledgments

This project received funding from Google PhD Fellowship and Volkswagen Foundation. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the funding organizations.

References

[1] Wouter M. Bergmann Tiest and Astrid M. L. Kappers. 2009. Cues for Haptic Perception of Compliance. *IEEE Transactions on Haptics* 2, 4 (Oct. 2009), 189–199. doi:10.1109/TOH.2009.16

[2] Bernd Bickel, Moritz Bächer, Miguel A. Otaduy, Hyunho Richard Lee, Hanspeter Pfister, Markus Gross, and Wojciech Matusik. 2010. Design and fabrication of materials with desired deformation behavior. *ACM Trans. Graph.* 29, 4 (July 2010). doi:10.1145/1778765.1778800

[3] Bernd Bickel, Moritz Bächer, Miguel A Otaduy, Wojciech Matusik, Hanspeter Pfister, and Markus Gross. 2009. Capture and modeling of non-linear heterogeneous soft tissue. *ACM transactions on graphics (TOG)* 28, 3 (2009), 1–9.

[4] Heather Culbertson and Katherine J. Kuchenbecker. 2017. Importance of Matching Physical Friction, Hardness, and Texture in Creating Realistic Haptic Virtual Surfaces. *IEEE Transactions on Haptics* 10, 1 (Jan. 2017), 63–74. doi:10.1109/TOH.2016.2598751

[5] Donald Degraen, Bruno Fruchard, Frederik Smolders, Emmanouil Potetsianakis, Seref Güngör, Antonio Krüger, and Jürgen Steimle. 2021. Weirding Haptics: In-Situ Prototyping of Vibrotactile Feedback in Virtual Reality through Vocalization. In *The 34th Annual ACM Symposium on User Interface Software and Technology (UIST '21)*. Association for Computing Machinery, New York, NY, USA, 936–953. doi:10.1145/3472749.3474797

[6] Donald Degraen, Michal Piovarči, Bernd Bickel, and Antonio Krüger. 2021. Capturing Tactile Properties of Real Surfaces for Haptic Reproduction. In *The 34th Annual ACM Symposium on User Interface Software and Technology (UIST '21)*. Association for Computing Machinery, New York, NY, USA, 954–971. doi:10.1145/3472749.3474798

[7] Haiwei Dong, Yu Gao, Hussein Al Osman, and Abdulmotaleb El Saddik. 2015. Development of a Web-Based Haptic Authoring Tool for Multimedia Applications. In *2015 IEEE International Symposium on Multimedia (ISM)*. 13–20. doi:10.1109/ISM.2015.71

[8] Alireza Fathi, Ali Farhadi, and James M. Rehg. 2011. Understanding egocentric activities. In *2011 International Conference on Computer Vision*. 407–414. doi:10.1109/ICCV.2011.6126269 ISSN: 2380-7504.

[9] Chris Harrison, Hrvoje Benko, and Andrew D. Wilson. 2011. OmniTouch: wearable multitouch interaction everywhere. In *Proceedings of the 24th annual ACM symposium on User interface software and technology (UIST '11)*. Association for Computing Machinery, New York, NY, USA, 441–450. doi:10.1145/2047196.2047255

[10] Ali Israr and Ivan Poupyrev. 2011. Tactile brush: drawing on skin with a tactile grid display. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '11)*. Association for Computing Machinery, New York, NY, USA, 2019–2028. doi:10.1145/1978942.1979235

[11] Ali Israr, Siyan Zhao, Kaitlyn Schwalje, Roberta Klatzky, and Jill Lehman. 2014. Feel Effects: Enriching Storytelling with Haptic Feedback. *ACM Trans. Appl. Percept.* 11, 3 (Sept. 2014), 11:1–11:17. doi:10.1145/2641570

[12] Kevin John, Yinan Li, and Hasti Seifi. 2024. AdapTics: A Toolkit for Creative Design and Integration of Real-Time Adaptive Mid-Air Ultrasound Tactons. In *Proceedings of the CHI Conference on Human Factors in Computing Systems (CHI '24)*. Association for Computing Machinery, New York, NY, USA, 1–15. doi:10.1145/3613904.3642090

[13] Erin Kim and Oliver Schneider. 2020. Defining Haptic Experience: Foundations for Understanding, Communicating, and Evaluating HX. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems (CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–13. doi:10.1145/3313831.3376280

[14] Hyunju Kim, Sanghwa Hong, Junki Kim, Taesoo Jang, Woontack Woo, Seongkook Heo, and Byungjoo Lee. 2021. RealityBrush: an AR authoring system that captures and utilizes kinetic properties of everyday objects. *Multimedia Tools and Applications* 80, 20 (Aug. 2021), 31135–31158. doi:10.1007/s11042-020-09332-4

[15] Hwan Kim, Minhwan Kim, and Woohun Lee. 2016. HapThimble: A Wearable Haptic Device towards Usable Virtual Touch Screen. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. Association for Computing Machinery, New York, NY, USA, 3694–3705. doi:10.1145/2858036.2858196

[16] Sunjun Kim and Geehyuk Lee. 2013. Haptic Feedback Design for a Virtual Button Along Force-Displacement Curves. In *Proceedings of the 26th annual ACM symposium on User interface software and technology (UIST '13)*. Association for Computing Machinery, New York, NY, USA, 91–96. doi:10.1145/2501988.2502041

[17] Katherine J. Kuchenbecker, Joseph Romano, and William McMahan. 2011. Haptography: Capturing and Recreating the Rich Feel of Real Surfaces. In *Robotics Research*, Cédric Pradalier, Roland Siegwart, and Gerhard Hirzinger (Eds.). Springer, Berlin, Heidelberg, 245–260. doi:10.1007/978-3-642-19457-3_15

[18] Jochen Lang, Dinesh K. Pai, and Robert J. Woodham. 2002. Acquisition of Elastic Models for Interactive Simulation. *The International Journal of Robotics Research* 21, 8 (Aug. 2002), 713–733. doi:10.1177/027836402761412458

[19] Stefan Leutenegger, Simon Lynen, Michael Bosse, Roland Siegwart, and Paul Furgale. 2015. Keyframe-based visual–inertial odometry using nonlinear optimization. *The International Journal of Robotics Research* 34, 3 (March 2015), 314–334. doi:10.1177/0278364914554813

[20] James R. Lewis. 2018. The System Usability Scale: Past, Present, and Future. *International Journal of Human–Computer Interaction* 34, 7 (July 2018), 577–590. doi:10.1080/10447318.2018.1455307

[21] Yi-Chi Liao, Sunjun Kim, Byungjoo Lee, and Antti Oulasvirta. 2020. Button Simulation and Design via FDVV Models. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems (CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–14. doi:10.1145/3313831.3376262

[22] Steve Mann, Kris M. Kitani, Yong Jae Lee, M. S. Ryoo, and Alireza Fathi. 2014. An Introduction to the 3rd Workshop on Egocentric (First-Person) Vision. In *2014 IEEE Conference on Computer Vision and Pattern Recognition Workshops*. 827–832. doi:10.1109/CVPRW.2014.133

[23] S.A. Mascaro and H.H. Asada. 2001. Photoplethysmograph fingernail sensors for measuring finger forces without haptic obstruction. *IEEE Transactions on Robotics and Automation* 17, 5 (Oct. 2001), 698–708. doi:10.1109/70.964669 Conference Name: IEEE Transactions on Robotics and Automation.

[24] Kouta Minamizawa, Yasuaki Kakehi, Masashi Nakatani, Soichiro Mihara, and Susumu Tachi. 2012. TECHTILE toolkit: a prototyping tool for design and education of haptic media. In *Proceedings of the 2012 Virtual Reality International Conference (VRIC '12)*. Association for Computing Machinery, New York, NY, USA, 1–2. doi:10.1145/2331714.2331745

[25] Dinmukhammed Mukashev, Nimesha Ranasinghe, and Aditya Shekhar Nittala. 2023. TactTongue: Prototyping ElectroTactile Stimulations on the Tongue. In *Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology (UIST '23)*. Association for Computing Machinery, New York, NY, USA, 1–14. doi:10.1145/3586183.3606829

[26] Dinesh K. Pai, Kees van den Doel, Doug L. James, Jochen Lang, John E. Lloyd, Joshua L. Richmond, and Som H. Yau. 2001. Scanning physical interaction behavior of 3D objects. In *Proceedings of the 28th annual conference on Computer graphics and interactive techniques (SIGGRAPH '01)*. Association for Computing Machinery, New York, NY, USA, 87–96. doi:10.1145/383259.383268

[27] Xun Qian, Fengming He, Xiyun Hu, Tianyi Wang, and Karthik Ramani. 2022. ARnnotate: An Augmented Reality Interface for CollectingCustom Dataset of 3D Hand-Object Interaction Pose Estimation. In *Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology*. 1–14.

[28] Hamid Roham, Siamak Najarian, Seyed Mohsen Hosseini, and Javad Dargahi. 2007. Design and fabrication of a new tactile probe for measuring the modulus of elasticity of soft tissues. *Sensor Review* 27, 4 (Jan. 2007), 317–323. doi:10.1108/02602280710821452

[29] P. V. Sabique, Ganesh Pasupathy, and Sivaramakrishnan Ramachandran. 2024. A data driven recurrent neural network approach for reproduction of variable visuo-haptic force feedback in surgical tool insertion. *Expert Systems with Applications* 238 (March 2024), 122221. doi:10.1016/j.eswa.2023.122221

[30] Oliver Schneider, Karon MacLean, Colin Swindells, and Kellogg Booth. 2017. Haptic experience design: What hapticians do and where they need help. *International Journal of Human-Computer Studies* 107 (Nov. 2017), 5–21. doi:10.1016/j.ijhcs.2017.04.004

[31] Oliver Schneider, Siyan Zhao, and Ali Israr. 2015. FeelCraft: User-Crafted Tactile Content. In *Haptic Interaction: Perception, Devices and Applications*, Hiroyuki Kajimoto, Hideyuki Ando, and Ki-Uk Kyung (Eds.). Springer Japan, Tokyo, 253–259. https://doi.org/10.1007/978-4-431-55690-9_47

[32] Oliver S. Schneider, Ali Israr, and Karon E. MacLean. 2015. Tactile Animation by Direct Manipulation of Grid Displays. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology (UIST '15)*. Association for Computing Machinery, New York, NY, USA, 21–30. doi:10.1145/2807442.2807470

[33] Jeffrey L. Schoner, Jochen Lang, and Hans-Peter Seidel. 2004. Measurement-Based Interactive Simulation of Viscoelastic Solids. *Computer Graphics Forum* 23, 3 (2004), 547–556. doi:10.1111/j.1467-8659.2004.00786.x

[34] Hasti Seifi, Sean Chew, Antony James Nascè, William Edward Lowther, William Frier, and Kasper Hornbæk. 2023. Feellustrator: A Design Tool for Ultrasound Mid-Air Haptics. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (CHI '23)*. Association for Computing Machinery, New York, NY, USA, 1–16. doi:10.1145/3544548.3580728

[35] Hasti Seifi, Matthew Chun, Colin Gallacher, Oliver Schneider, and Karon E. MacLean. 2020. How Do Novice Hapticians Design? A Case Study in Creating Haptic Learning Environments. *IEEE Transactions on Haptics* 13, 4 (Oct. 2020), 791–805. doi:10.1109/TOH.2020.2968903

[36] Matti Strese, Lara Brudermueller, Jonas Kirsch, and Eckehard Steinbach. 2020. Haptic Material Analysis and Classification Inspired by Human Exploratory Procedures. *IEEE Transactions on Haptics* 13, 2 (April 2020), 404–424. doi:10.1109/TOH.2019.2952118

[37] Paul Strohmeier, Seref Güngör, Luis Herres, Dennis Gudea, Bruno Fruchard, and Jürgen Steimle. 2020. bARefoot: Generating Virtual Materials using Motion Coupled Vibration in Shoes. In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology (UIST '20)*. Association for Computing Machinery, New York, NY, USA, 579–593. doi:10.1145/3379337.3415828

[38] Onejae Sul, Eunsuk Choi, and Seung-Beck Lee. 2017. A Portable Stiffness Measurement System. *Sensors* 17, 11 (Nov. 2017), 2686. doi:10.3390/s17112686

[39] Youjin Sung, Kevin John, Sang Ho Yoon, and Hasti Seifi. 2025. HapticGen: Generative Text-to-Vibration Model for Streamlining Haptic Design. In *Proceedings of the 2025 CHI Conference on Human Factors in Computing Systems*. 1–24.

[40] Youjin Sung, Rachel Kim, Kun Woo Song, Yitian Shao, and Sang Ho Yoon. 2024. HapticPilot: Authoring In-situ Hand Posture-Adaptive Vibrotactile Feedback for Virtual Reality. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 7, 4 (Jan. 2024), 179:1–179:28. doi:10.1145/3631453

[41] Yuta Takeuchi, Sho Kamuro, Kouta Minamizawa, and Susumu Tachi. 2012. Haptic duplicator. In *Proceedings of the 2012 Virtual Reality International Conference (VRIC '12)*. Association for Computing Machinery, New York, NY, USA, 1–2. doi:10.1145/2331714.2331749

[42] Ka Po Maggie Tang, Kit Lun Yick, Pui Ling Li, Joanne Yip, King Hei Or, and Kam Hong Chau. 2020. Effect of Contacting Surface on the Performance of Thin-Film Force and Pressure Sensors. *Sensors* 20, 23 (Jan. 2020), 6863. doi:10.3390/s20236863

[43] Anke van Oosterhout, Miguel Bruns, and Eve Hoggan. 2020. Facilitating Flexible Force Feedback Design with Feelix. In *Proceedings of the 2020 International Conference on Multimodal Interaction (ICMI '20)*. Association for Computing Machinery, New York, NY, USA, 184–193. doi:10.1145/3382507.3418819

[44] Gabriela Vega, Valentin Martinez-Missir, Dennis Wittchen, Nihar Sabnis, Audrey Girouard, Karen Anne Cochrane, and Paul Strohmeier. 2024. vARitouch: Back of the Finger Device for Adding Variable Compliance to Rigid Objects. In *Proceedings of the CHI Conference on Human Factors in Computing Systems (CHI '24)*. Association for Computing Machinery, New York, NY, USA, 1–20. doi:10.1145/3613904.3642828

[45] Yoichi Watanabe, Yasutoshi Makino, Katsunari Sato, and Takashi Maeno. 2012. Contact Force and Finger Angles Estimation for Touch Panel by Detecting Transmitted Light on Fingernail. In *Haptics: Perception, Devices, Mobility, and Communication*, Poika Isokoski and Jukka Springare (Eds.). Springer, Berlin, Heidelberg, 601–612. doi:10.1007/978-3-642-31401-8_53

[46] Anusha Withana, Daniel Groeger, and Jürgen Steimle. 2018. Tacttoo: A Thin and Feel-Through Tattoo for On-Skin Tactile Output. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology (UIST '18)*. Association for Computing Machinery, New York, NY, USA, 365–378. doi:10.1145/3242587.3242645

[47] Chang Xu, Yuxiang Wang, and Gregory J. Gerling. 2021. An elasticity-curvature illusion decouples cutaneous and proprioceptive cues in active exploration of soft objects. *PLOS Computational Biology* 17, 3 (March 2021), e1008848. doi:10.1371/journal.pcbi.1008848

[48] Wenzhen Yuan, Siyuan Dong, and Edward H Adelson. 2017. Gelsight: High-resolution robot tactile sensors for estimating geometry and force. *Sensors* 17, 12 (2017), 2762.