Reel Feel: Rich Haptic XR Experiences Using an Active, Worn, Multi-String Device

Nathan DeVrio
Human-Computer Interaction Institute
Carnegie Mellon University
Pittsburgh, Pennsylvania, USA
ndevrio@cmu.edu

Chris Harrison
Human-Computer Interaction Institute
Carnegie Mellon University
Pittsburgh, Pennsylvania, USA
chris.harrison@cs.cmu.edu

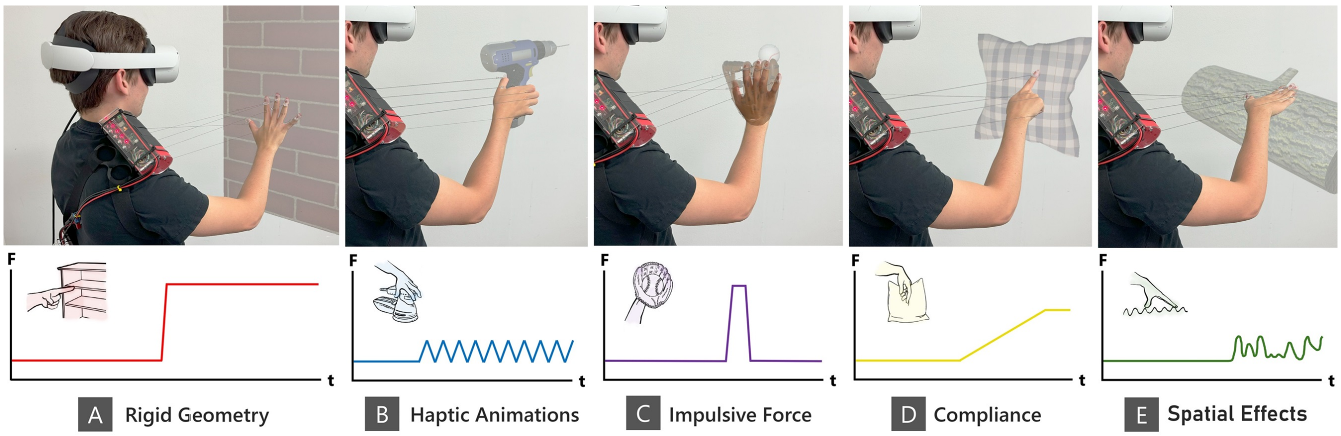


Figure 1: We developed Reel Feel, a novel shoulder-worn haptic device that uses strings attached to the fingertips and motorized reels to render a variety of haptic effects, including rigid geometry (A), haptic animations (B), impulsive force (C), compliance (D), and texture (E). Here we show example interactions for each effect (top), and the fingertip force waveform (bottom).

Abstract

While many haptic systems have been demonstrated for use in virtual and augmented reality, they most often enable a single category of feedback (e.g., kinematic breaking, object compliance, texture). Combining prior systems to achieve multi-dimensional effects is unwieldy, expensive, and often physically impossible. We believe this is holding back the ubiquity of rich haptics in both the consumer and industrial AR/VR/XR domains. In this work, we describe Reel Feel, a novel, shoulder-worn haptic system capable of rendering rigid geometry, object-bound haptic animations, impulsive forces, surface compliance, and fine-grained spatial effects all in one unified, worn device. Our design aimed to minimize the weight on the hands (<10 g), where a system's mass is most felt, as many prior systems are heavy gloves and exoskeletons. Finally, we sought to keep the device practical, being self-contained, low-cost, and low enough power to be feasible for consumer adoption with a high degree of mobility. In a user evaluation, our device rated better than a conventional vibrotactile baseline for all qualitative measures (immersion, realism, etc.) and allowed participants to more accurately discern object compliance and fine-grained spatial effects.

CCS Concepts

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

Keywords

Haptics; Virtual Reality; Augmented Reality; Wearable; Interaction techniques

ACM Reference Format:
Nathan DeVrio and Chris Harrison. 2025. Reel Feel: Rich Haptic XR Experiences Using an Active, Worn, Multi-String Device. In *CHI Conference on Human Factors in Computing Systems (CHI '25), April 26–May 01, 2025, Yokohama, Japan.* ACM, New York, NY, USA, 20 pages. https://doi.org/10.1145/3706598.3713615

CHI '25, Yokohama, Japan

ACM ISBN 979-8-4007-1394-1/25/04
https://doi.org/10.1145/3706598.3713615

1 Introduction

Over the past decade, research and commercial development of augmented and virtual reality (AR/VR) systems has advanced rapidly. In 2024, there are systems on the market such as the Meta Quest 3 and Apple Vision Pro that provide convincing visuals and spatial audio, all of which help to create immersive virtual experiences. However, the ability to *feel* realistic haptic sensations when interacting with virtual objects is still lacking in all mainstream systems. Of course, haptic sensations of shape, weight, and texture are some of our most important ways of reasoning about the world. A system that can render such sensations could have a significant impact on increasing realism and immersion.

Accordingly, with a problem of this importance, innumerable approaches have been explored in both academia and industry, which have attempted to bridge the outstanding haptics gap between virtual and real. A common theme is that systems tend to develop a complex solution that can render only a single sensation (e.g., rigid geometry) [19, 20, 25, 32]. The few exceptions, such as the commercial HaptX system [81], can render force across the hands at different scales (macro and micro), but suffer from increased system complexity, size, and cost that limits user comfort, mobility, and ultimately widespread adoption. In addition, while some systems for cutaneous sensations are unobtrusive enough to conceivably be combined with systems for kinesthetic sensations (including Reel Feel) [30, 64, 73, 86], kinesthetic-focused systems are often bulky and cannot be combined to render more than one sensation [18, 31, 37, 78, 79, 83, 85]. We see the high bulk and cost of existing solutions, as well as their narrow palette of sensations, as a key factor holding back VR haptics from becoming more ubiquitous.

The haptic device we describe in this work, which we call Reel Feel, contributes an improvement on wearable haptic systems by offering multiple haptic effect categories in a single system, while also minimizing bulk, cost, and complexity. Reel Feel is a self-contained device that is worn on the user's shoulder and capable of being battery powered and portable. Haptic sensations are rendered through a set of strings attached to each of the user's fingers that extend back to a shoulder device, where they are wound around a computer-controlled, high-torque, brushless DC motor.

We create effects by programmatically changing the speed and torque of our motors in a continuous manner. For example, by continuously varying these forces, we can create sensations of compliant objects, and by modulating them, we can render spatial effects. By adjusting the programmatic inputs, our system is able to render five different types of haptic sensations: rigid geometry, haptic animations, impulsive forces, compliance, and fine-grained spatial effects (Figure 1). In addition to operating on their own, these sensations can be used as "building blocks" and combined to make more complex haptic experiences.

In summary, Reel Feel offers a unique set of capabilities that sets it apart from prior work. First and foremost, its reel design allows the system to render much larger forces on the user's hand than other wearable systems of similar size. This enables haptic effects that were not previously possible in this form factor. Second, compared to other systems, our device can exert significantly more output force relative to its low power. Finally, while many previous systems from the literature have excelled at rendering single haptic effects (see overview in Figure 2), Reel Feel improves upon them by being able to render five unique categories at once, all while retaining a practical form factor.

2 Literature Review

Creating convincing haptics for AR/VR has been a long standing focus in the HCI and robotics literature. However, solutions for the challenges involved in creating a device that is both practical and convincing remain elusive. These challenges are even more severe for wearable haptic systems like ours. As such, it is most common for a system to focus on a single haptic sensation, such as object compliance or texture.

In this section, we review a variety of systems that focused on rendering each of the expressive categories that Reel Feel renders. A summary of key systems and their advantages and disadvantages compared to Reel Feel is provided in Figure 2. In our review, we focus exclusively on wearable haptic systems because they are the most similar to Reel Feel and suffer unique constraints in form factor, power, and weight that grounded haptic systems do not. At the end of this section, we will review systems (not exclusively wearable) that use cable-driven haptic techniques.

2.1 Wearable Haptic Devices By Expressive Category

2.1.1 Rigid Geometry. One of the most fundamental haptic sensations is reaching out and feeling objects. Upon contact, users might wish to explore the shape, contours, and edges. In this subsection, we include all of these properties under the category of *rigid geometry*.

More than any other category, geometry has seen the most attention in past research. Although there have been waves of research investigating this area since the 1990s, a modern wave of HCI research began in the mid-2010s [6] and resulted in Wolverine, developed by Choi et al. and later improved upon by Grabity [19, 20]. Both systems used a simple design with unidirectional brakes attached to the fingers to restrict motion and render shape. While many systems have since improved upon this idea, the concept of halting finger motion to render a rigid surface has remained.

A significant successor was DextrES, developed by Hinchet et al. [32]. While Wolverine and Grabity were limited in that the entire device was semi-rigid, DextrES significantly increased dexterity by placing electrostatic brakes on the back of each finger. These brakes were flexible, allowing the fingers to remain mobile, but could also become rigid when powered. This is the basis for the hand exoskeleton class of devices that also includes systems such as the early CyberGrasp [8, 24, 66], and later Dexmo [29, 69], ELAXO [90], RML Glove [53], Haptic PIVOT [46], HaptX [81], PalmEx [15], and Son and Park's device [68].

Hand exoskeletons have the advantage that they have to render smaller normal forces because the fingers can exert less force than in our case where forces are compounded from the wrist and arm back up to the shoulder. The trade off is that exoskeletons put more weight on the forearm, which will tire users, and can generally only render gripped objects (but not world-grounded, whole-arm kinesthetic effects, such as knocking on a door).

Beyond exoskeletons, other systems have used different actuators to render geometry. CLAW by Choi et al. used a mechanized servo arm on the index finger that could actively move to render other sensations beyond shape, such as texture [21]. More experimentally, Teng et al. used pneumatic inflatables to render geometry [76], while Lopes et al. and Tanaka et al. used electrical muscle stimulation (EMS) [52, 73]. Advantages of tactile systems using EMS are that they may not require mechanically moving parts [39] or direct skin attachment [73]. Finally, Wireality, developed by Fang et al. [25], used a ratcheting cable mechanism, highly related to our system. We discuss this system in detail in the coming subsection on cable-driven haptic devices.

2.1.2 Haptic Animations. Handheld devices that can render haptic animations (e.g., motor vibrations, mechanical clicks from a handheld weapon) are commonplace, with many existing VR controllers integrating ERM or LRA motors for vibrotactile feedback [22, 23]. In the academic literature, alternative techniques such as synchronized arrays of ERMs and LRAs in controllers [10, 62] and on wristbands [58] have been used to create spatially animated effects. Other less conventional techniques include animated microtactile arrays [43, 64], pneumatic bellows to dynamically squeeze the wrist [88], a motorized lead screw [60], and hand sensations using transcranial-magnetic-stimulation of the brain [72].

2.1.3 Impulsive Forces. Next we discuss haptic systems that focus on rendering reactive, impulsive interactions, such as hitting a tennis ball or firing a weapon. These impulsive forces are often large in magnitude and short in duration (i.e., an impulse). In the past, one category of systems has mounted force feedback devices on VR controllers that were programmed to time forces with virtual impulses. Examples of feedback devices that have been used include propellers [31, 37], compressed air jets [18, 78, 83], solenoids [75], voice coil actuators [71], weight shifting props [89], and flywheels [85]. Compared with these techniques, Reel Feel is relatively compact and can render similar forces without the need for air lines or energy storage.

A separate category of systems includes some of the exoskeletons discussed in the previous section on rigid geometry. Son and Park's exoskeleton and PalmEx had small motors on the back of the hand that could not just arrest finger movement, but also actively pull backwards to apply impulses [15, 68]. Haptic PIVOT, on the other hand, used a motorized mass which could swing into the user's hand to apply impulses, like catching a falling object [17]. These systems had a form factor more similar to Reel Feel, however they differ in that Reel Feel can render larger forces with its larger motors, and can render impulses through the entire arm by being mounted to the shoulder.

2.1.4 Texture and Spatial Surface Effects. Three common approaches have been used in the past for rendering spatial effects, such as object texture. The first of these involves rubbing an artificial surface against the fingertip that is meant to mimic what the real surface of the virtual object might feel like. The Haptic Revolver, by Whitmire et al. [84], did exactly this — spinning a textured disc beneath the index finger to render micro-textures like rough surfaces and macro-textures like larger bumps or holes.

A second, and more popular approach is to place a miniature grid array of actuating elements beneath each fingertip that can be moved to simulate texture. TextureTouch by Benko et al. [11], HaptiVec by Chen et al. [17], Fluid Reality by Shen et al. [64], and even the commercial HaptX gloves [81] all take this approach, albeit with different actuation mechanisms. This technique is advantageous because it allows for a nearly infinite amount of convincing textures to be rendered by correctly programming the tactile array. However, its primary drawback is that the associated actuation mechanisms (either linear actuators or fluid pumps) are bulky, with the exception of Fluid Reality.

The final approach is to generate haptic textures with a vibrotactile actuator. Strohmeier et al. pioneered this technique where they

	Quest 2 Controller [19]	Wireality [21]	Dexmo [25]	PalmEx [55]	Multi-Vibes [53]	Haptic PIVOT [55]	Texture-Touch [11]	DextrES [28]	CLAW [18]	Tasbi [49]	HapCube [37]	TORC [41]	ElasticVR [65]	HaptX G1 [67]	Fluid Reality [55]	Haptic Handshake [10]	Cyber-Grasp [55]	RML Glove [55]	Reel Feel
Haptic category: Rigid geometry		✓	✓	✓				✓	✓					✓			✓	✓	✓
Haptic category: Haptic animations	✓				✓					✓	✓			✓	✓	✓	✓	✓	✓
Haptic category: Impulses						✓							✓				✓	✓	✓
Haptic category: Compliance								✓		✓	✓	✓	✓		✓	✓	✓	✓	✓
Haptic category: Texture							✓		✓			✓		✓	✓	✓	✓	✓	✓
Worn position	held in palm	shoulder, hands-free	back of hand exoskeleton	back of hand exoskeleton	held in palm	wrist	held in palm	back of hand exoskeleton	held in palm	wrist	between fingers	between fingers	lower arm	glove, lower arm, back	glove, finger tips	held in palm	back of hand exoskeleton	back of hand exoskeleton	shoulder, hands-free
Feedback point	palm	finger tips, whole hand	finger tips	finger tips, palm	palm	palm	index finger	thumb & index finger	thumb & index finger	wrist	thumb, index finger	thumb, index, & middle fingers	whole hand	whole hand	finger tips	thumb, palm	finger tips	index & middle fingers	finger tips, whole hand
Actuator type	vibrotactile motor	rachet gear with solenoid pawl + strings	servo motors + linkages	servo motors + linkages	vibrotactile motors	motorized swinging mass	actuating pin array	electro-static brake, piezo-electric actuator	servo motor, voice coil actuator	tensioning band, linear resonsant actuators	voicecoil actuators	vibrotactile motor, voice coil actuator	motorized elastic band with dynamic brake	pneumatic microfluidic actuators	electro-osmotic pump arrays	pneumatic airbag, electro-vibration membrane, vibrotactile motor	motorized cables + linkages	motorized cables + linkages	gimbal motor reels + strings
Max. force (per finger)	n/r	183 N (static)	0.3 N•m (torque)	1.2 N (active)	n/r	3.5 N (active)	n/r	20 N (static)	30 N (active)	18 N (active)	0.4 N (active)	n/r	14 N (active)	178 N (static)	< 1 N (active)	n/r	12 N (active)	10 N (active)	5.7 N (active)
Power	n/r	2.19 W (peak)	5 W (mean)	n/r	n/r	n/r	4 W (mean)	< 0.12 W (peak)	5 W (peak)	< 2 W (mean)	2.1 W (mean)	n/r	n/r	300 W (peak)	2.23 W (mean)	3.6 W (mean)	79.2 W (mean)	n/r	4.6 W (mean)
Weight on hand	150 g	11 g	270 g	~150 g	n/r	188 g	600 g	16 g	420 g	< 200 g	19 g	n/r	150 g	450 g	147 g	220 g	> 454 g	180 g	6 g
Approx. cost	$75	$35	$200	n/r	$200	n/r	n/r	n/r	$150	n/r	n/r	$100	n/r	$5,500	$300	n/r	$103,000	n/r	$240

Figure 2: High-level overview of highly-related haptic systems. Comparable numbers drawn from published materials as best possible, but please consult individual papers for specifics.

placed the finger on a vibrotactile actuator and varied its feedback when sliding it along an instrumented slider [70]. The first two approaches render texture by presenting shapes to the fingertips to vary normal forces within the finger pad. The third approach is different in that it solely uses vibrotactile actuation; it is also the most similar to how Reel Feel renders texture. We point to the bodies of work referenced by Strohmeier et al. that show perception of texture is linked to vibrations felt by the Meissner and Pacinian corpuscles [12, 13, 44, 47, 70, 87]. The same arguments suggest Reel Feel's method of pulling the fingers at a high frequency can be used to generate the perception of texture. However, we acknowledge with one variable force per finger, our "texture-like" effects are coarser than ones that can be rendered by systems with dense arrays of haptic pixels [11, 64, 81].

2.1.5 Object Compliance. Of all categories, there have been the least systems specifically focused on object compliance. Tao et al. made a system with silicone pads on the fingertips like ours, however their goal was to change perceived softness of real-world objects, not create haptics for virtual ones [74]. More relevant examples are HapCube, developed by Kim et al. [41], and TORC, developed by Lee et al. [48]. Both systems used a similar device, held between the fingers in a pinch grip, that contained two flat surfaces with a vibrating mass underneath. HapCube used oscillating magnets while TORC used motors. These systems were clever in that they rendered compliance without directly rendering the object's normal forces while being squeezed. However, the particular grip the devices required meant it was challenging to adopt to additional haptic use cases. This highlights two advantages of Reel Feel in keeping the hands free and rendering multiple sensations with a single actuator.

2.2 Cable-Driven Haptic Devices

In terms of actuation, the systems most similar to Reel Feel are those that also use tension from cables to generate haptic effects. Cable tension haptics were first realized in feedback systems for virtual environments in the VIDET project from the late 1990s [9]. One of the systems from this project, WireMan, was even portable, operating by pulling on the index finger using one or three cables driven from a backpack device [14].

2.2.1 Caged Cable Haptics. Until recently, the most popular approaches for cable-driven haptics have placed the hands in rigid cages and rendered 3D forces by pulling on the fingers with motors mounted around the periphery [33, 42]. The most prolific project using this technique, SPIDAR, explored numerous cage and cable designs to render different types of sensations [36, 49, 51, 56, 57].

2.2.2 Wearable Cable Haptics. More recently, HCI research has begun advancing lightweight, wearable, cable-driven haptics. The first was Wang et al.'s system which mounted a fixed-length cable to a VR headset and rendered surfaces at the end of the cable, where tension feedback could be felt [82]. Wireality, developed by Fang et al. [25] improved upon this idea with a mechanized approach. Their system used cables from each of the fingers to a device worn on the shoulder that could arrest the cables using a pawl and ratchet design. In this way, all five fingers could freely move through space unencumbered until they individually encountered a virtual object. Wireality is the most similar system to Reel Feel, however, it was only able to arrest the fingers and render rigid geometry using tension, while our system can actively pull the fingers, enabling four additional sensations. Furthermore, once the the ratchet locks, there is no ability for the system to release the lock, meaning curved and more complex surface geometries are not possible, nor are textures, animations, impulsive fores or compliance. The ability of Reel Feel to continuously vary string forces without locking, thereby creating more diverse haptics, is its significant and central advantage over Wireality.

More recently, Achberger et al. developed two cable systems called STRIVE and STROE [3, 4]. STRIVE used a similar technique to Wireality and improved the design by streamlining the hardware and showing how its reels can also be anchored in the environment, like a hybrid cage. STROE on the other hand strung a cable between a VR controller and a motorized pulley on the foot to simulate object weight in VR.

2.2.3 Wearable Elastic Haptics. A final class of "cable" haptics uses elastic bands for compliance and impulsive forces. Achibet et al. rendered compliance by tethering the palm to an elastic band on the shoulder and modified perception using retargeting and illusions [5]. ElasticVR by Tsai et al. used a retractable spool (much like Wireality) on the palm and an elastic band, which can be tensioned to change its compliance [79]. Finally, ExoInterfaces by Tsetserukou et al. also attached an elastic band to the arm and wrist, and used motors for retraction to render strong impulsive forces [80].

Compared to past cable-driven haptic devices, Reel Feel differentiates itself by allowing users to feel a wide array of different haptic sensations using a single self-contained device [3, 4, 25, 50]. The most closely related work — Wireality — cannot render vibrations, whole arm kinesthetic feedback, compliance, or textures. Compared to SPIDAR and other mounted systems, Reel Feel also has a compact and wearable form factor that enables portability [33, 42, 50] and does not encumber the user's movement [3, 4]. Finally, the disadvantage of many of these systems is that they are designed to only work for a narrow set of interactions, like simulating weight [3] or one force aligned with the arm (no fingers) [79]. In contrast, Reel Feel enables a broad set of interactions with independent forces on all fingers and a generous range of motion.

3 Implementation

Reel Feel required extensive iteration of both hardware and software components. When combined, they enable a number of different

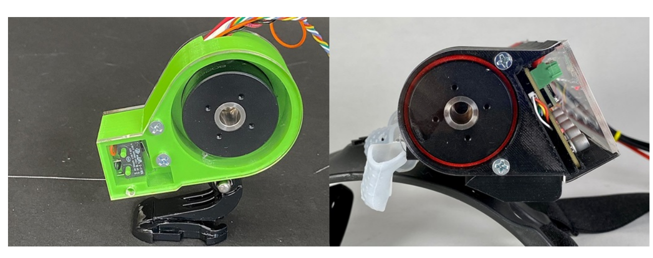


Figure 3: Close ups of the reel design for the initial single-finger (left) and finalized five-finger prototypes (right).

Figure 4: The final Reel Feel prototype in action, with relevant dimensions provided. During use, the device is worn on the shoulder, with the strings leading down to the hand.

haptic sensations that can be felt by the wearer. In this section we detail their technical background and implementation.

3.1 Haptic Device Hardware

The core operation of Reel Feel involves attaching a string to each finger and creating pulling forces to induce haptic sensations on the fingertips. These pulling forces were created by winding each string around a motorized spool, and programming the motor to wind to produce a force. All five motor spools along with the associated control electronics were housed in a case that was worn on the shoulder via an adjustable harness. This harness consisted of a curved, plastic plate that sat on the shoulder and was secured using fabric straps around the torso.

We chose to use the shoulder as the mounting point for our system due to its unobstructed path to the hands, so as to not impede the strings. However, more importantly (and unlike most other systems [11, 20, 21, 32, 41, 48, 84]), we also placed virtually no mass on the hands or arms, improving user comfort. Over the entire body, the shoulders have been shown to be one of the best locations for placing wearables without excessive fatigue [27].

A photo of our initial, single-finger prototype is shown in Figure 3. In this early version, we used angle values from motor encoders to estimate finger position to know when to render sensations. We also experimented with a limit switch mechanism to determine when the string was not taut and needed to be reeled in. Although functional, the click of the switch activating introduced a noticeable tactile bump that distracted from the smooth movement of the motors. The switch was also only able to detect when reeling needed to begin and not when to stop. Given these shortcomings, in our final prototype, we kept the use of encoders, but removed the switches and instead used fingertip tracking from cameras on the VR headset to maintain proper tension and remove slack.

Photos of our final prototype are shown in Figures 3 and 4. This version used nylon fishing string for cables, which were attached to silicone finger caps. Each cable was measured two meters long, so as not to inhibit any user's field of reach. The cables were wound around the hub of the motor and constrained using two 3D-printed reel guards (shown in Figure 5a). The spool housing for each motor was also 3D printed and contained a guiding hole for the cable. All five motors, their spools, and the control electronics were housed in a compact enclosure that weighed 710 g and was attached to a shoulder harness. For our prototype, we built a device for one hand. For a complete system, we envision twin devices being worn on each shoulder to provide haptics for both hands.

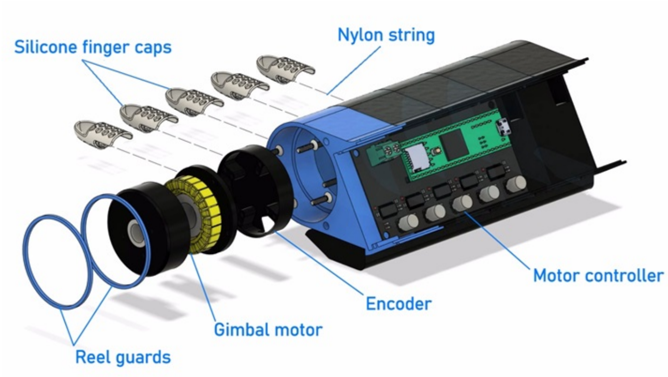
3.2 Motor Selection

An important decision in designing the hardware of our system was to decide what motor to use. In our prototype device we used three-phase brushless DC (BLDC) "gimbal" motors. This type of motor is most commonly used in camera stabilizers and drones. Compared to other types of motors, the advantages of this class of BLDC motors are that they have high efficiency, run very smoothly (i.e., low cogging torque), and can deliver high torque. This comes from the fact that the magnet and coil design allows such motors to operate at maximum torque continuously throughout the entire rotation of the rotor [61]. Gimbal motors are a subclass of BLDC motors that have increased in popularity and availability (and reduced in cost) over the past decade with growth in the high-tech camera and drone markets. Compared to "standard" BLDC motors, such as those used in RC planes, gimbal motors have stators wound with many more turns which gives them a higher reactance. As a result, they take a smaller current to produce a larger torque, especially at low velocities [16]. This also means that even small BLDC motors can deliver considerable power for their size. This was an ideal property for our application since we wished to optimize the torque to weight ratio through our motor choice.

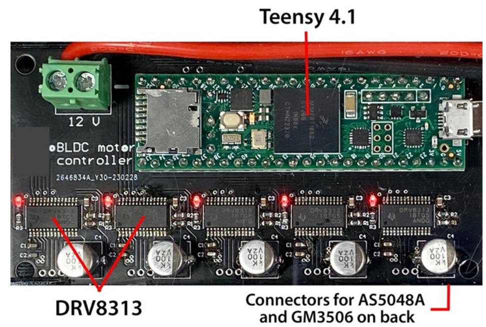
During our design phase, we experimented with three different motors, with torque values at a 1 A load ranging from 5.8 N·cm to 39.2 N·cm, and which weigh 39.5 g to 204 g, respectively [35, 77]. For our final prototype, we selected the GM3506 BLDC gimbal motor, which offers 14.7 N·cm torque at 1 A, and weighs 64 g each [34]. These can be purchased online for under $20 in single quantities, and less in higher volumes. We found this motor's ratio of torque to weight to be a good balance, where the total weight of our prototype (five motors per hand) was not too distracting for users, while still delivering strong kinematic effects.

3.3 Motor Control Electronics

To drive the BLDC motors, we developed a custom control board (shown in Figure 5b). At the heart of this board is a Teensy 4.1 microcontroller unit (MCU). The MCU is connected over USB to a PC that is running the VR software from which it receives serial commands. This MCU was chosen for its 625 MHz clock rate so it can run the motor control loop fast, and because it fully utilizes the 480 Mbit/s bandwith of USB 2.0. This allowed it to keep up all of the serial commands we were outputting from our Unity demo on the PC which was running at 70 FPS. On our board, the MCU controls each motor using a DRV8313 which has three individually controllable half-H-bridges to drive the three phases of the motor at up to 12 V. Each motor also has its own AS5048A magnetic encoder which are connected over SPI.



(a) Exploded diagram of all Reel Feel hardware components.



(b) Our motor control board receives commands from a PC and is used to drive the motors and receive data from their encoders.

Figure 5: Details of the shoulder-mounted Reel Feel hardware.

3.4 Prototype Cost

Our prototype cost ~$240 in parts. By far, the most expensive components are the BLDC motors and their encoders that account for over 83% of the total cost. Other components, including the Teensy MCU, motor driver chips, nylon string, and wires make up the rest. If created at a mass scale, we would expect cost for all of these components to be reduced, certainly under $200, and perhaps even under $100.

3.5 Haptic Control Firmware

To control the haptic hardware that we created, we developed a layer of control firmware that ran on the MCU. We used a closed-loop PID control algorithm, adapted from the SimpleFOC library [67], to set motor parameters. In more detail, the algorithms we used took encoder angles and a command for motor voltage as inputs to a closed feedback loop to control first torque, then velocity. We opted to use voltage instead of current as the input to our control loop because although current is more accurate, it requires more processing and thus would have led to a slower update rate [67].

As a part of our control firmware, we used pulse-width modulation via the H-bridges to vary the effective voltage that drove each motor. Drive voltage was linearly proportional to the output force felt on the fingertip, thus whenever we wanted to render a stronger sensation, we used a higher voltage. At a drive voltage of 7 V, motor load current is maxed out, so the torque cannot be increased higher than this. In our piloting, we also found the impulse forces at 7 V at the limit of what could be felt without feeling jarring or too strong. In order to generate any force, the motors needed at least 0.5 V applied, thus our resultant range for haptic control was 0.5-7 V.

To simplify upstream development, we also created firmware functions that took a waveform type (square, sine) and frequency as arguments and rendered vibrations by pulsing the voltage driven to the motors. These functions were used to render some sensations of spatial effects and haptic animations in demos. All the other sensation types were rendered by setting motor voltages in the upstream software.

3.6 Maintaining Tension

An important requirement for our system is to keep the strings under tension at all times to minimize latency for force interactions. We do this automatically by using encoder values and tracking the fingertip positions using the cameras on the front of the VR headset. By default, we assume strings are tensioned and remain so when the user pushes forwards. As a result, strings only become un-tensioned when moving the hand back toward the torso. Using cameras, we detect when this occurs independently for each fingertip and begin reeling in with high speed, but low torque. Reeling stops when we detect the encoder values stop changing (i.e., no more string is reeling in).

3.7 Physical Material Modeling

To better understand how to render forces with our system, we conducted an investigation modeling two example materials. In Figure 6, we show a plot mapping motor voltage to output force for a single string. For a single motorized string, the maximum output force that can be applied to the finger is 5.7 N. Also in Figure 7, we show a mapping between the deformation of two example compliant materials, a block of insulating foam and a pillow, and the normal force applied to the pushing hand. The Young's Moduli of the materials were 8000 and 5600 N/m^2 for the foam and pillow respectively.

In Figure 7, we combined the two plots from Figure 6 and also included lines for the maximum motor force for one- and five-finger strings to show the maximum material deformations that we can simulate accurately. As expected, as the compliance of a material increases, the maximum deformation we can accurately simulate also increases. Additionally, while sometimes we cannot generate enough force on a single fingertip to accurately simulate normal forces at higher finger pressures (greater deformation), when multiple fingers are used, our range of physically accurate simulation increases.

3.8 VR Software

Separate from the Reel Feel hardware, we also needed software to interface with the VR headset (Meta Quest 2), render a virtual scene,

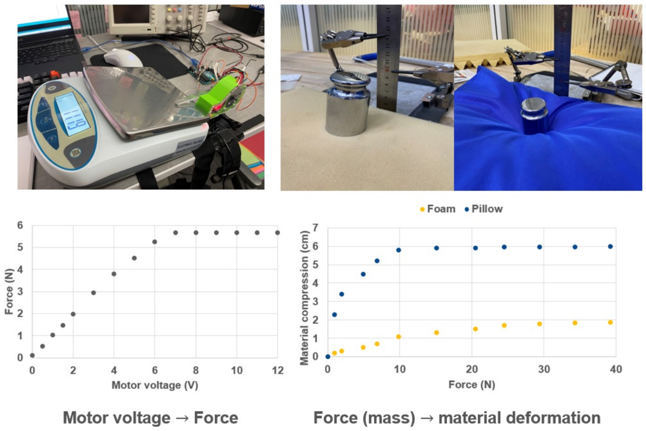


Figure 6: Our setup for physical material modeling. Each column is a matched photo and plot for an experiment. On the left, we found a mapping between motor voltage and output force. On the right, we found a mapping between applied force and material deformation.

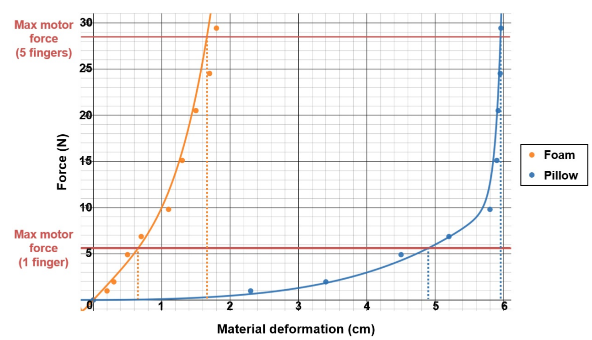


Figure 7: A combined plot from both material modeling experiments: maps from material deformation to normal force for two materials. This mapping was used to inform a realistic output force for each string.

and determine when to activate haptic sensations. At a high level, this system's purpose is to render a scene in VR featuring several interactable objects, track the position of the user's hands using the Quest 2's built-in cameras, and determine when a finger has collided with a virtual object to trigger a haptic sensation. For fingertip tracking, we used the Meta XR package in Unity, and tracking was not diminished or disabled by the strings and silicone finger caps. The first two parts of this software were relatively straightforward using built-in Unity components. Determining when to trigger a haptic sensation, and with what intensity, was a more challenging problem. Our very first test involved rendering rigid objects. Here we set up a collider on the surface of the virtual object, and when the finger hit the collider, we triggered a closed-loop control to keep the motor at that angle until the finger exited the collider.

This worked well for rigid objects, but was hard to adapt to compliant ones. We initially tried rendering pulling forces as soon as the finger entered the object, and increasing the force the further the finger went in. This is actually how our first physical model worked where we changed the force using a function mapping from compression to motor voltage obtained empirically from the real-world material (from subsection on Physical Material Modeling). However, in practice, we found such an approach led to behavior where the torque would drastically increase as soon as the finger passed the object's surface boundery. This caused the finger to jerk backwards and exit the collider. Upon exiting, the applied force was removed, causing the finger to jerk forwards, creating a oscillatory effect. To counter this effect, we created an alternative model, not based off real-world forces, where we increased a collider's bounds 1 cm beyond the object's surface, and linearly increased the force once entered. A visualization of this is shown in Figure 8. In this way, once the user's finger reached the object's surface, the force had already built up in a more subtle, continuous manner. This eliminated the previous force oscillations, and made the end-user experience more comfortable and realistic. The slope value of the linear function was determined based on the stiffness of the material.

We note that all spatial interactions (rigid geometry & fine-grained spatial effects) are triggered by tracking of hand keypoints. As a result, haptic resolution is chiefly constrained by the resolution of the headset's fingertip tracking and the resolution of the collider/texture image used. Figure 8 shows a coarse convex collider for clarity, however, higher-fidelity ones can be used to increase perceived haptic resolution.

The compliant material model described above formed the foundation for all other sensations. Rigid geometry was rendered by using a model with a very high stiffness value. The other three sensations (spatial effects, animations, and impulsive force) were rendered by superpositioning additional voltage functions (such as a square wave) characteristic of that sensation on top of the compliant model.

3.9 Potential Challenges for Force Simulation

Reel Feel can render any force that can be represented by a ray from the shoulder device. In practical use, some forces do not follow this path. For example, a user does not always point their finger perpendicular to a surface they are touching. When this path cannot be traced precisely, Reel Feel will still render an appropriate force providing a simulate of the sensation. In our studies, we found the effect is convincing up to ~45° misalignment. There are some less common interactions, such as touching the backside of an object, that Reel Feel cannot render. VR designers would need to note such constraints when designing interactions with our system. We discuss these cases and potential solutions further in the Limitations and Future Work section.

3.9.1 Wire Tangling. A concern of our system's design is that fingers may cross over, causing the strings to tangle or knot. In practice, this does not occur due to the physical anatomy of the hand — if a user does cross their fingers, they have to reverse the same path to uncross them, which causes the wires to uncross (i.e., knots are not possible). Our system also constantly maintains tension in the strings so they will not tangle from slack.

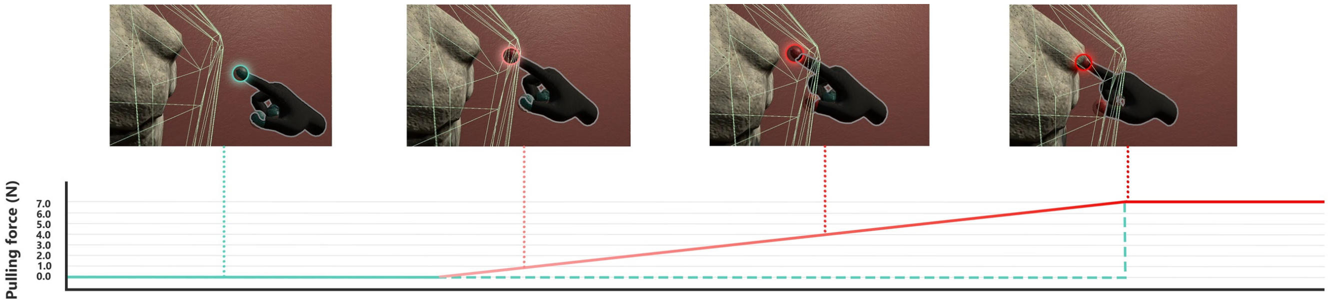


Figure 8: Using custom colliders, motor pulling force increases linearly as a user approaches an object from a few centimeters out so that the transition to full force is smooth by the time they contact the surface. This helps eliminate any jerky behavior.

3.9.2 Finger Curling. Two other uncommon situations could present a challenge to our string-based system. One involves actions such as making a fist to grab an object, or grabbing and rotating a door handle. In these, the motion of curling fingers or a twisting arm causes the strings to come into contact with the user's skin. If the strings briefly touch the skin, the user feels a stimulus that is not represented in the virtual world. This is undesirable, however, the sensation is small relative to the motor force, so the haptic illusion is not significantly weakened. In the majority of normal use, fingers are not curled and the strings never touch the skin.

3.9.3 Arms Crossing Over. Even less common is if the user is using two Reel Feel devices, one on each hand, and crosses their arms over. Although we could not find a study measuring how often this exact behavior occurs during typical VR use, we reference a study by Ahuja et al. [7] on the range of motion of handheld controllers while playing popular VR games and highlight that less than 2.5% of the time did even one arm cross the midpoint of a user's torso. This suggests crossed-arm interactions in AR/VR are relatively rare. Despite all of this, even if the arms were to cross, given the strings are always connected at two endpoints, they will not tangle unless deliberately wrapped around the other arm.

3.10 System Performance

In this last subsection, we describe focused performance evaluations of different properties of our system. All properties were measured using the mentioned 0.5 - 7 V voltage range, and we provide additional information on our calculations where appropriate.

3.10.1 Actuation Force. The minimum and maximum forces we can render on each fingertip are 0.5 and 5.7 N, respectively. Forces were measured using an electronic load cell. When all five motors are activated at maximum voltage, up to 28.5 N of force is applied to the hand. For reference, humans typically apply a few newtons of force when pressing a mechanical button (1 cm radius) with a finger, and roughly 10 N of force when two-finger gripping and lifting a heavy object (0.8 kg) [38]. Thus our system's applied finger forces covers a useful and practical range, without the ability to harm the user.

3.10.2 Reeling speed. At the lowest voltage setting (0.5 V) the strings are reeled in at a speed of 38.3 cm/s. If the motor voltage is increased to the maximum (7 V), the spools can be reeled at a max speed of 228.5 cm/s. All speeds were measured using motor encoders. For comparison, the torsional springs used in Wireality provide a 0.78 N retraction force [25]. Whenever we need to reel in the strings, we use the max reel speed. The average length of a person's reach is ~80 cm. Thus, if a person brought their hand from max reach to their shoulder instantly, it would still only take ~350 ms to tension. Given this latency, differences in arm length do not noticeably affect the experience.

3.10.3 Latency. Latency was measured in four parts: (1) Quest hand tracking, (2) Time from collider event to command sent to Teensy, (3) USB serial speed, (4) Time from voltage commanded to motor to value change on encoder. The Quest 2 hand tracking used in our prototype offered a latency of under 27 ms [1, 55]. Latency for the rest was 14 ms for Unity sending the Teensy command, 50 us for USB serial and ~5 ms for the encoder to change leading to an overall system latency of ~46 ms. In rare cases where the user is moving quickly and the motors need to catch up to tension, there can be a few extra milliseconds of latency. This effect can be seen in Figure 9, which shows latency for various system states.

3.10.4 Power Consumption. At maximum force, one finger (driver + motor) requires approximately 1.2 A @ 7 V (8.4 W). However, this peak is only ever approached when rendering intense haptics that are brief (e.g., rapidly decelerating a fast-moving arm colliding with a virtual rigid surface). When actuating all fingers, more typical haptic effects (e.g., medium strength touches to surfaces, tactile exploring textures) consume around 21.6 W of power. In the default state, motors are not powered on, and the device consumes < 0.1 W.

If we consider a hypothetical minute of VR interaction, with 10 haptic events rendered on all five fingers lasting one second each, and where the reels are actively retracted during all intervening periods. Each one-second haptic event consumes 6.0 mWh × of power, while each second of reeling consumes 0.33 mWh of power, for a total average power consumption of 6.0 mWh × 10 seconds + 0.3 mWh × 50 seconds = 76.67 mWh / minute. Thus, if our system included two small lithium-ion cells (e.g., Samsung 25R 18650 [59], each rated at 9 Wh with a maximum continuous discharge rate of 20 A), this would provide enough power for ~3.9 hours of runtime.

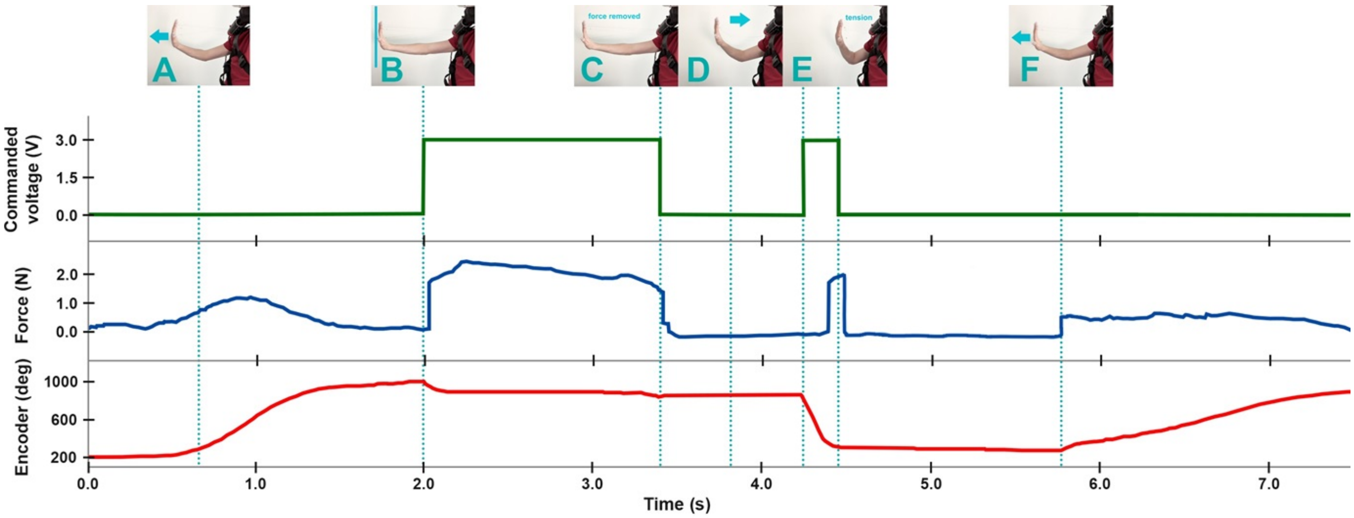


Figure 9: Measured force and encoder values plotted with commanded voltage for one motor. Traces are aligned vertically to show latency. The sequence of events is: (A) extending arm with string at tension, (B) finger arrested on object contact, (C) rendered force removed, (D) arm pulled back, (E) string tensioning engaged then complete, and (F) extending arm again.

4 Expressive Capabilities

In this section, we detail examples of VR interactions where Reel Feel can be used to enhance the user experience. These interactions are divided into five broad categories, based around the different categories of sensations our system can render, along with a brief discussion of combining multiple sensations together. Reference Figure 10 for visualizations of what the output motor voltage signal looks like for examples from each category.

4.1 Rigid Geometry

In a typical VR scene, in addition to interactable items and characters, there are often many static objects that make up the background environment such as walls, handles, furniture, and more. Normally, such objects are either placed out of the way, or provide no feedback when a user's tracked hands run into one. Reel Feel changes this by allowing the user to feel simulated normal forces on their hand, just like what they would expect if touching similar objects in the real world. Due to its ability to render independent forces on each fingertip, our system is capable of simulating not only flat surfaces, but also curvature and intricate surface features.

4.1.1 Surface Interactions. The primary category of rigid feedback in VR is interactions with surfaces. Here, surfaces include not just large flat objects like tables and walls but also furniture, trees, rocks, and other static environmental features. Examples scenes showcasing these interactions for a bookcase and columns are shown in Figure 11.

4.1.2 Object-Mediated Surface Interactions. The second type of rigid surface capability involves situations where users interact with virtual surfaces through an intermediate object or tool. Example interactions of this type might include striking a nail with a hammer, swinging a bat and hitting a baseball, and writing on a whiteboard with a marker. A demo of a hammer strike can be seen in the Video Figure.

4.2 Haptic Animations

Reel Feel can also render haptic animations, when a user picks up or interacts with a virtual object. Unique from the previous sensations which are confined to surfaces, these animated effects move with the hand in 3D space and can add life to otherwise static objects.

4.2.1 Object-Bound Haptic Animations. One use case is attaching haptic animations to objects in VR, such as a running washing machine, a beating heart, and an orbital power sander (all shown in Figure 11).

4.2.2 "Clicks" and Other UI Widget feedback. A more specialized, but high-value use case is attaching confirmatory haptic feedback to interactive widgets, such as buttons, keys, sliders, switches, etc. In the Video Figure, we show a demo of the tactile "click" of a mechanical keyboard.

4.3 Impulsive Forces

While haptic animations can cover many cyclic virtual effects that exert forces on the hand, there are other times when an object hits the hand or a handheld object creates a reactive force. In these cases, our system is able to render strong and instantaneous impulse forces. For instance, we can create sensations like catching a basketball pass, holding a door closed to prevent a monster from getting into a room, and recoil from a plasma blaster (examples scenes shown in Figure 11).

4.4 Compliance

While a large portion of virtual objects often have rigid geometries, many other objects that are compliant in the real world would feel jarring and unbelievable if rendered in a rigid manner. Reel Feel

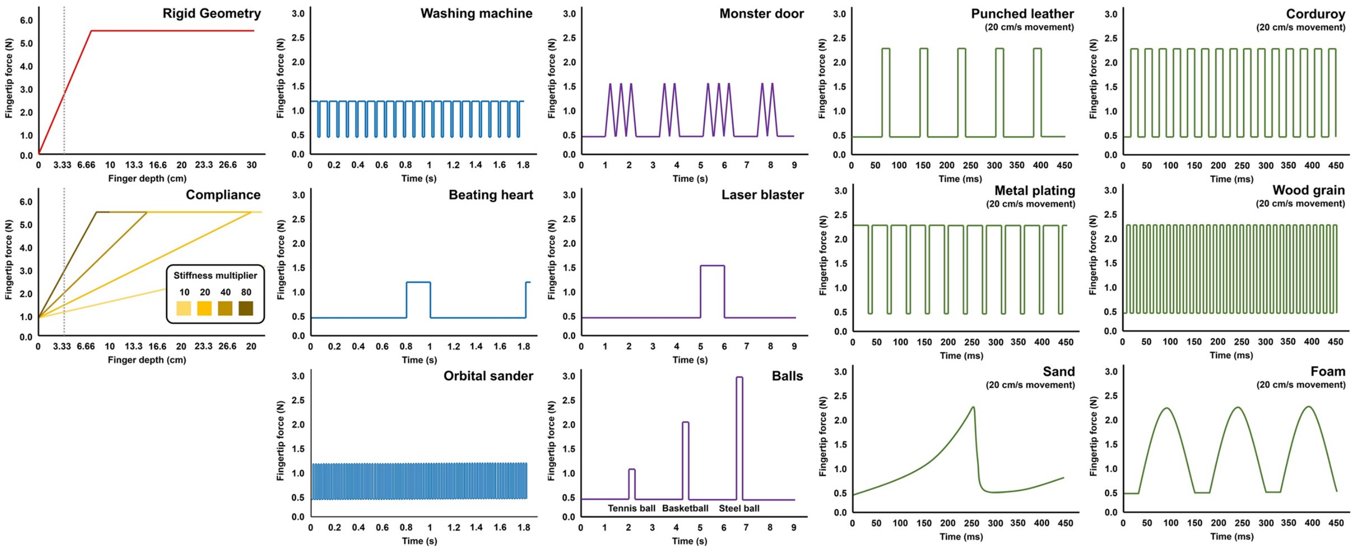


Figure 10: Output motor force for a single finger while rendering all five expressive capabilities. The examples shown represent all haptic demos used in our Evaluation. Beyond these, our system is capable of rendering many more demos within each expressive category.

allows such objects to be rendered by continuously adjusting the normal force feedback as the fingers press into the surface. This capability allows for more realistic interaction with many types of compliant object not possible with a rigid-only system. Examples scenes for a pillow and sponge are shown in the Video Figure.

4.5 Fine-Grained Spatial Effects

By modulating drive voltage in quick succession, Reel Feel can render vibrotactile sensations on the fingertips and thus simulate various surface effects and even coarse textures. As illustrated in Figures 1 and 10, these are often higher frequency than our other effects. In the Related Work section, we discussed prior evidence for how whole-finger vibrations alone can be perceived by humans as texture, even without dense arrays of actuators.

We note this category is related to the previous category of Haptic Animations, which also employed a similar frequency range. However, whereas our Haptic Animations varied in time, this category's haptic effects vary in space, specifically as a user translates their fingers across a surface.

We implemented fine-grained spatial effects by assigning virtual objects not only a visual (conventional) texture, but also an invisible "haptic texture". The latter is a 2D grayscale image that maps pixel brightness to motor torque. As the user translates their fingers across a surface, we continually lookup where the finger keypoint lies in the haptic texture, and then command that motor's torque according to that pixel's grayscale value. In this way, each finger can receive spatially coherent haptic feedback. We constructed the grayscale images for each texture by taking the color image and transforming it such that bright and dark spots correspond to high and low areas of the texture, respectively. Output from this process for textures we tested are shown in Figure 12.

How "fine-grained" our spatial sensations were depended on the resolution of the image texture used and the speed of finger translation. In typical use, image resolution could be so high that it was not a limiting factor. Finger speed did matter because our Unity backend had an update rate of 70 FPS. This meant we could only render textures while the finger traveled less than 70 pixels a second before pixels were skipped. Meissner's corpuscles in the skin respond to vibrations between ~30-80 Hz, and thus were well activated [70]. Pacinian corpuscles, on the other hand, respond to vibrations between ~250-350 Hz [70]. Although we did not test such high-frequency effects in our demos, our electronics are capable of rendering up to 200 Hz vibrations if programmed directly.

4.6 Combining Sensations

Finally, while all of Reel Feel's expressive capabilities can enable interesting use cases on their own, they can also be creatively combined to create new types of interactions. Notably, until the voltage limit of a motor is reached, all of the sensations can be superimposed on top of one another. We built an example scene demonstrating such combinations, shown in the Video Figure. In this scene, a user is on a mountain bike and feels smaller continuous bumps/vibration from riding on a gravel path, then sudden impulsive jerks of the handlebars when they hit boulders.

5 Evaluation Procedure

To evaluate how users perceived our systems haptic sensations, we conducted a user evaluation consisting of two studies. Our first study evaluated all five of Reel Feel's haptic categories (versus a controller-based vibrotactile baseline), capturing questionnaire responses from participants. Our second study focused on object properties and the discriminability of our haptic stimuli, where user

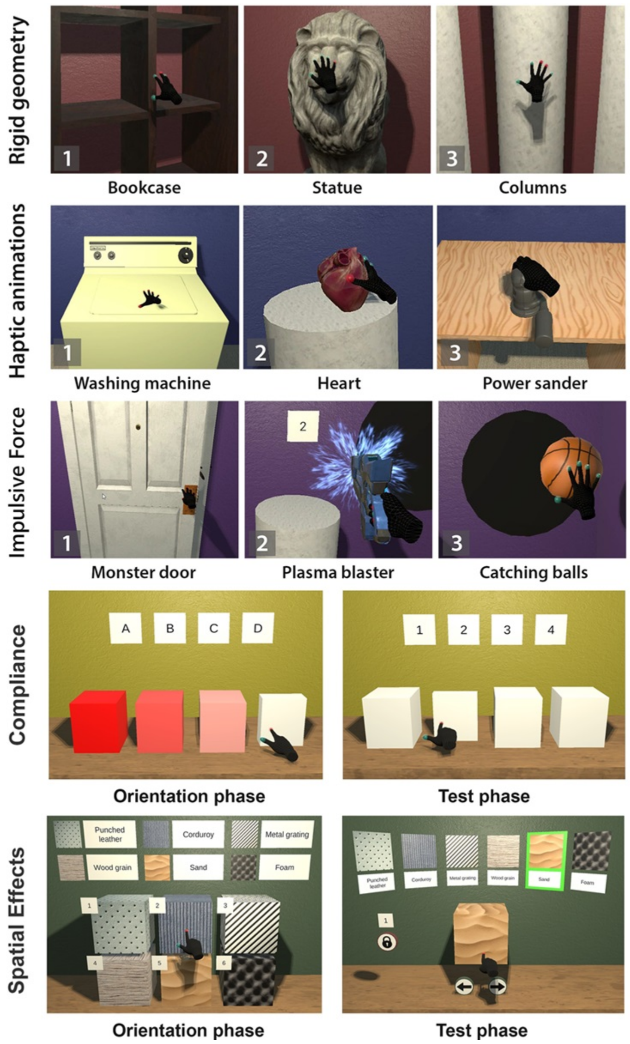


Figure 11: Demos used for each of the haptic categories in our user study. For geometry, animations, and impulsive forces (on the left), we created three exemplary demos to showcase each sensation (numbered 1-3 in each row). For compliance and spatial effects (on the right), we had participants complete tasks that consisted of a training and test phase.

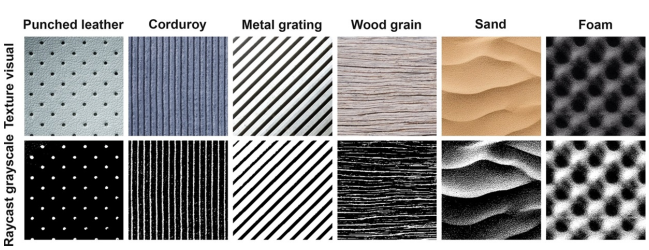


Figure 12: Visuals used in the spatial effects task alongside their corresponding grayscale "haptic texture" images used for rendering force.

accuracy could be assessed. Briefly here, our goal was to investigate the following research questions:

(RQ1): How well do our individual haptic categories rate in regards to realism, immersion, fun, and preference over a conventional vibrotactile baseline?

(RQ2): How well does overall the haptic experience rate on the five measures of harmony, expressivity, autotelics, immersion, and realism?

(RQ3): Can Reel Feel render differentiable and orderable object compliances (i.e., soft to firm)?

(RQ4): Can Reel Feel provide distinct and differentiable fine-grained spatial effects, especially vs. a vibrotactile baseline?

Both studies were conducted back-to-back, with a break in between, which we conducted with 10 participants (mean age 27.7, 7 male, 3 female). Six of our participants reported having prior experience in VR and three of them had used a dedicated haptic device in VR before. The entire session lasted one hour and paid $25 in compensation. The studies were conducted in a typical office space where participants stood in the center of a 2 × 2 m^2 open area. Participants wore the Reel Feel device on their right shoulder and a Meta Quest 2 headset, which we also used for hand tracking.

5.1 Baseline Selection

To provide a point of reference for our system's performance, we also ran our studies on a baseline haptic device. For our baseline, we used the Touch Controllers included with the Meta Quest 2. The controller uses an internal vibrotactile motor to generate haptic effects, which is controllable through an API [54]. This baseline was chosen because of its ubiquity and familiarity as the "standard" haptic experience in mainstream VR. The vibrotactile motor can only reasonably render one haptic dimension (vibrations/animations). However, we were able to use it to approximate the other four categories by changing the vibration intensity and timing, allowing it to be used for all five experiments.

Other baselines that we considered were bare hands (mid air, no haptics) and an emulation of Wireality [25]. Bare hands were a poor choice, because in lacking haptics, meaningful results for any of the test tasks could not be collected, and for the survey questions the contrast between feeling haptics and not when measuring properties such as realism and immersion would make our system's superior rating a straw man comparison. We also considered using Reel Feel to emulate the behavior of Wireality, the closest comparison system, as a baseline. However, Wireality only renders rigid geometry, so as a baseline it would be inappropriate for evaluating 4 out of 5 categories. For rigid geometry, the way we would emulate touch contact (by rendering max force upon object contact) is functionally the same as Reel Feel's implementation, and thus the two systems would be the same. Thus, we determined this baseline was also not meaningful. Of the options available, controllers with vibrotactile feedback offered the most feasible and useful point of comparison.

5.2 Study 1: Qualitative Feedback on Reel Feel Interactions

In the first study, users explored virtual interactions from *all five* haptic categories while using the Reel Feel device. To recap, these categories included **(1) rigid geometry**, **(2) haptic animations**, **(3) impulsive forces**, **(4) compliance**, and **(5) spatial effects**. The categories were specifically chosen to represent the array of different haptic sensations that our system could render in VR. For categories 1-3, we developed three demo interactions for users to play with and explore what kind of sensations our system could render for that interaction type. For categories 4 and 5, participants provided qualitative feedback after completing the tasks in Study 2. Descriptions and images of the demo interactions are shown in Figure 11; the interactions were presented in the same fixed order (1-3 in Figure 10) for all participants. Plots showing the force functions experienced in each interaction, including waveform, frequency, and duty cycle where appropriate, are shown separately in Figure 10. While experiencing the demos, we also asked participants to speak aloud their thoughts on each interaction and we share excerpts in our Results section.

5.2.1 Questionnaire 1.1 — Category-Specific Feedback. The first questionnaire we used in this study investigated our second research question. We used seven questions modeled from Fang and Harrison [26] and Shen et al. [65]. The questions consisted of 1) The *controller* feedback examples felt realistic; 2) The *string* feedback examples felt realistic; 3) The controller *feedback* examples made me feel more immersed in the scene; 4) The *string* feedback examples made me feel more immersed in the scene; 5) The *controller* feedback examples were fun; 6) The *string* feedback examples were fun; and 7) I preferred the *controller* feedback over *string* feedback examples. Like when used in the past [65], to mitigate order effects, we counterbalanced ordering of the "controller" and "string" feedback conditions between participants.

All questionnaire items were rated on a 7-point Likert scale ranging from -3 (strongly disagree) to +3 (strongly agree); see [28] for more details on this measure. We asked this questionnaire after users experienced all three demos or the object property task for *both* the "controller" and "string" device. The order that participants used the controller or Reel Feel to experience the demos or complete the property tasks (controller first, Reel Feel second, or vice-versa) was changed between participants to mitigate order effects.

5.2.2 Questionnaire 1.2 — Pan-Category Feedback. The second questionnaire used in this study investigated our first research question. After participants experienced the demos and completed property tasks for all five categories, we asked them this questionnaire about their overall experience using the haptic devices.

Our driving inspiration behind the second questionnaire was the Haptic Experience (HX) Model developed by Kim et al. [40]. This model is used to evaluate the user experience of a haptic system using five constructs, including: harmony, expressivity, autotelics (purposeful), immersion, and realism. Harmony measures how well a sensation fits with other senses, expressivity measures distinction between effects, autotelics measures how "good" a sensation feels in and of itself, immersion measures how immersed the user is, and realism measures how similar to real life a sensation feels. Work by Sathiyamurthy et al. has shown the validity of this model [63] and in the broader literature it has become a popular and accepted model for evaluating systems such as ours [64]. It is for these reasons that we decided the five factors of the HX model were appropriate measures to evaluate the performance of the Reel Feel experience. We used twenty-two questions taken directly from Sathiyamurthy et al. (Figure 3) [63] that evaluated each of the HX factors. The full question list can be found in the Appendix. For each question, it was asked first for the "controller" device, then for the "string" device. Like before, all questionnaire items were rated on a 7-point Likert scale, and the ordering of "controller" and "string" questions was flipped between participants.

5.3 Study 2: Object Property Tasks

In our second study, we were interested in answering our third and fourth research questions, namely, how well does our device allow users to discern and differentiate different properties of virtual objects, specifically object compliance and fine-grained spatial effects on object surfaces. These two categories were particularly expressive and thus were appropriate for stimuli ordering/recognition tasks. In addition, we specifically wanted to understand how much advantage Reel Feel might provide over a vibrotactile controller baseline. The objective of the tasks in Study 2 was to measure how discernible the sensations were from one another, such that it could enable ordering or recognition. Although the objective was not to measure how closely the properties matched the real world, this was captured separately through the HX questionnaire at the end of the task (and in Study 1; realism measures).

5.3.1 Study Task 2.1 — Compliance. The compliance task began with a brief orientation where participants could familiarize themselves with the task and the haptic feedback. Our procedure closely matches that used in recent work by Shen et al. [64], which also evaluated object compliance haptics. More specifically, during the orientation, participants were shown four cubes with increasingly dark shades of red. The darker the color, the firmer the object. See Figure 11 for an image of this setup. The virtual Young's Moduli for the four cubes tested were (in order) 19.6, 39.3, 78.5, and 157.0 kN/m^2. These specific compliance values were chosen to maximize the difference between different felt compliances and remain within the max force our system could render. The force functions used for each cube are shown in Figure 10.

After the participant felt confident they had a sense of the haptic effect, the experiment moved into the testing phase and the scene was reloaded, this time with all cubes the same color and the compliance ordering randomized. Participants could then feel all four cubes and we asked them to verbally rank the cubes in order from most to least firm. The visual effect for each cube was identical, and only compressed in a direct 1:1 mapping to 3D fingertip position. In this way, the cube visual did not reveal any information.

This entire task was completed using one device (either controller baseline or Reel Feel), before switching to the other. Like with Study 1, the starting order the devices was flipped between participants to mitigate order effects. At the end of the compliance task, participants were given a short verbal questionnaire (not requiring them to remove the VR headset) with the following questions drawn from the HX model [63]: E1, E2, H2, A4, which can be found in the Appendix. The use of these specific questions was inspired by same question set used by Shen et al. [64] in their similar studies of compliance and texture. For each question, we asked the question first for either the "controller" baseline or "string" device, based

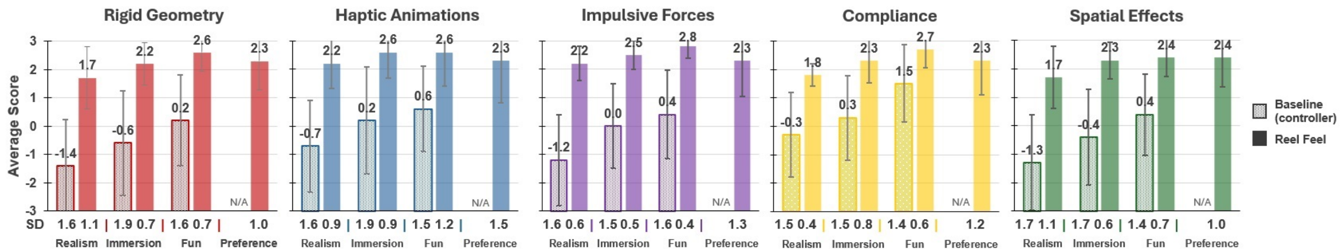


Figure 13: Mean Likert scores for the category-specific questionnaire in Study 1 using questions from Fang and Harrison [26]. Results are broken out for each haptic category. The final question on preference between Reel Feel and the controller baseline was only asked once and is only shown as a positive preference for Reel Feel. Error bars are standard deviation.

on which the participant experienced first, then asked the other condition.

5.3.2 Study Task 2.2 — Fine-Grained Spatial Effects. This task followed a structure similar to our compliance study task. In the orientation phase, participants were shown six cubes with different visual textures and fine-grained haptic effects that varied over space. A legend was also provided; setup seen in Figure 11, bottom left. Participants were allowed to familiarize themselves with the task and haptic effects. Our stimuli included *punched leather*, *corduroy*, *metal grating*, *wood grain*, *sand*, and *foam*. Four of these textures were inspired by those used by Shen et al. [64] in their texture task, and we created two new ones (*sand* and *foam*). As discussed in Section 3, the haptic patterns for each textured object were created by setting up an invisible grayscale "texture image" and using this akin to a lookup table mapping pixel intensity to motor force.

Following the orientation, participants moved to the test phase. A cube was placed directly in front of participants with a random fine-grained spatial haptic effect assigned per trial. Participants could cycle between the different visual textures using arrow buttons shown in VR. Their task was to find the visual texture that matched to the underlying fine-grained spatial haptic effect. A visual legend was provided in the back of the scene, but it was out of reach and participants could not consult it haptically. We note this procedure is nearly identical to the texture matching study procedure in Shen et al. [64]. Once satisfied, participants locked in their selection with a button press and the task moved to the next trial. In total, all six fine-grained spatial effects were presented two times each, in a random order, for a total of 12 trials.

Same as in our compliance task, participants completed the task first with one device condition, and then the other; the presentation of the conditions was counterbalanced between participants to mitigate order effects. At the end of the spatial effects task, participants were given the same verbal questionnaire as the compliance task.

6 Results & Discussion

In this section, we detail the results from our evaluation. For each study, we also examine whether the research questions of interest we outlined in the previous section were met. To conclude the section, we provide a brief general discussion on themes and trends we observed from participant feedback. Full results from our questionnaires are provided in the Appendix.

6.1 Study 1 Results

6.1.1 Category-Specific Questionnaire. To evaluate the results from our first study, we performed two separate analyses. First, we took the category-specific questions asked after participants interacted with each demo in a category and averaged the scores across all participants. These results are shown in Figure 13. The average score for Reel Feel was 2.31 (STD=0.29). All scores were greater than 1.7 (somewhat agree/agree), and were on average 2.31 points better than the average baseline score.

To evaluate significance, we ran a post-hoc Wilcoxon signed rank test on the effect of positive change in surveyed results from the baseline device to Reel Feel. For the category-specific questionnaire, we found all questions to be statistically significant ($p < 0.05$). The worst performing — though still significant — categories were *immersion* and *fun* for the haptic animations category. This was not surprising given haptic sensations between the controller baseline and Reel Feel are the most similar for haptic animations specifically.

Overall, participants gave the highest Reel Feel scores for impulsive forces (mean=2.45, STD=0.80). These high scores were fairly well distributed across the four dimensions. Participants strongly agreed that the impulsive force demos were the most fun (mean=2.8, STD=0.4), rating this the highest among all dimensions in all haptic categories. For the plasma blaster, which was consistently received well, players thought the strong recoil feedback was realistic and fun (P3, P4, P6, P7, P8, P10). The monster door was also well received, but users felt it was less realistic and immersive as "the sudden feeling I get interrupts your gameplay if you're in a game" (P10). Overall, users said this category was fun (P3, P6), felt good (P1, P3, P7, P9), and enjoyed when it felt more like a game (P1, P6).

The second highest-rated category, haptic animations, also had high scores for Reel Feel, similar to animations, but was less consistent (mean=2.43, STD=1.16). Many participants remarked that the washing machine and sander demos were the most realistic out of the entire study (P3, P4, P6, P7, P8, P9, P10). A large factor in the positive response to these demos was their high-frequency vibrations, with a participant remarking that "vibrations in the objects felt very similar to what they should feel like in reality" (P2). Although not a designed feature, rendering larger forces for animations also allowed users to feel some feedback in their shoulder, which they enjoyed and said increased realism (P6).

For the remaining three categories, participants gave very similar, but slightly lower average Reel Feel scores for rigid geometry

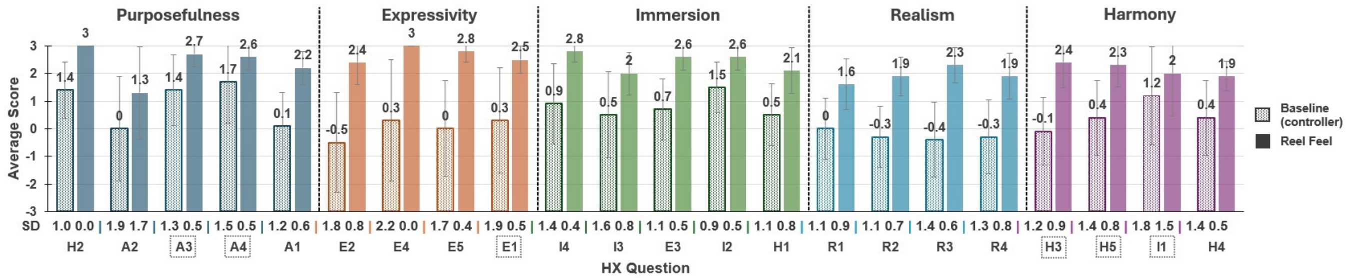


Figure 14: Mean Likert scores for the pan-category questionnaire asked at the end of Study 1 after participants had experienced all haptic categories. Questions are from the HX questionnaire used by Sathiyamurthy et al. [63] and are broken out by HX construct. Negatively loaded questions are marked with dashed boxes and were inverted for easier comprehension. Error bars are standard deviation.

(mean=2.20, STD=0.95), compliance (mean=2.23, STD=0.87), and texture (mean=2.20, STD=0.93). Compliance and texture will be discussed more in Study 2. For rigid geometry, realism received the lowest score (mean=1.7, STD=1.1). Notably, the variance was high, with some users enjoying the rigid sensations much more than others. Most participants mentioned they liked the columns the best, and said they could feel the curvature when touching them (P5, P7, P8, P10). Speaking on this, P7 said, "I like the big curve feeling on the column more than the little curves on the lion". Other participants also echoed that larger features felt better than smaller ones (P5, P7). One reason the realism and immersion scores for this category were dragged down had to do with the way we rendered collisions. In the example of the bookcase, if a user put their hand into shelf then collided with the side of a wall, the system would register their fingers as deep in the wall and strongly pull on them to return them to the surface. Multiple users felt this broke the realism and immersion (P9, P10).

Compared to the baseline, our device excelled in all dimensions for all five haptic categories. On average, the Reel Feel prototype scored 81.4% better for rigid geometry, 60.3% better for haptic animations, 74.1% better for impulsive forces, 39.3% better for compliance, and 72.0% better for texture. These results demonstrate that Reel Feel provides a significant advantage in realism, immersion, and fun compared to a vibrotactile controller and is the preferred haptic device. This answers RQ1. We also believe these results validate our string-based continuous force rendering approach and the benefit it provides.

Looking more broadly, we observed that participants rated haptic animations and impulsive forces the highest and spatial effects the lowest. This aligned with our expectations that our system, which can render one large, dynamic force per finger, was better at animations and impulses than fine-grained effects like texture. The lowest-rated Reel Feel device question was *realism* for geometry. Based on comments participants shared, we believe this was tied to how our software allowed users to (1) clip through geometry if they pressed too hard and (2) how their fingers were sharply pulled to the surface if they entered the side of an object. In the future, these issues could be remedied in software by locking finger visuals on surfaces and limiting strong haptics on the sides of objects.

6.1.2 Pan-Category Questionnaire. For our second analysis, we averaged scores from the larger HX questionnaire asked at the end of the user study. These results are shown in Figure 20. Wilcoxon results showed the positive effect of Reel Feel on survey answers was significant ($W < 2$, $p < 0.01$). When broken out individually, the only question that did not meet the threshold for significance was I1 ($n = 6$, $W = 2.5$, $p > 0.05$).

In general, all average scores for the Reel Feel device were greater than 1.3 (somewhat agree) and were on average 42.2% better than the average baseline score (vibrotactile controller condition), answering RQ2. Our system scored highest for the metrics of expressivity (mean=2.68, STD=0.57) and immersion (mean=2.42, STD=0.70), and the lowest for realism (mean=1.93, STD=0.82). The well-received questions for expressivity asked participants if feedback felt adequately variable and not too similar, while those for immersion asked participants if they felt the feedback increased their engagement and involvement with what they were doing.

Average scores for expressivity and immersion were above 2.0 for all categories, indicating that despite users finding some demos less immersive, that when considering the feedback in general, they believed it was very immersive (and expressive). Questions for realism asked if the feedback was believable and matched their expectations. This category also scored the lowest. Based on participant feedback, this was likely due to occasional sudden forces when not interacting with objects head on. Although tied to a limitation of our system's force direction, this was also an interaction we did not fully account for in our rendering software. Nevertheless, we believe through better tracking of the fingertip direction, this could be smoothed in the future.

6.2 Study 2 Results

6.2.1 Compliance Ordering Task. The results for the test phases of the compliance and spatial effects tasks are shown in Figures 15 and 16, respectively. Participants did extremely well on the compliance test and found it to be easier compared to the texture matching task. For each stiffness level of the cubes, we calculated an accuracy for how often that level was assigned the correct ranking position. The average accuracy was 95% (STD=15%) for the baseline controller ondition and 100% (STD=0%) for our Reel Feel device, with only

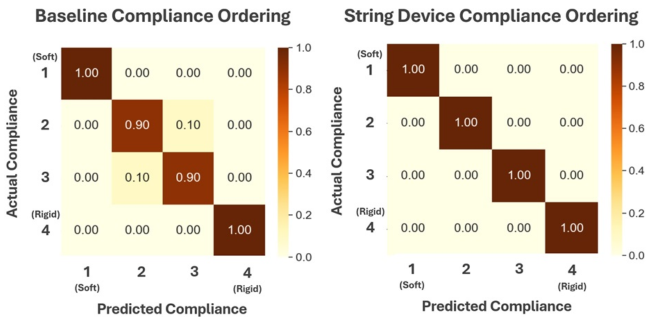


Figure 15: Confusion matrices for the compliance ordering task for the controller baseline (left) and Reel Feel (right).

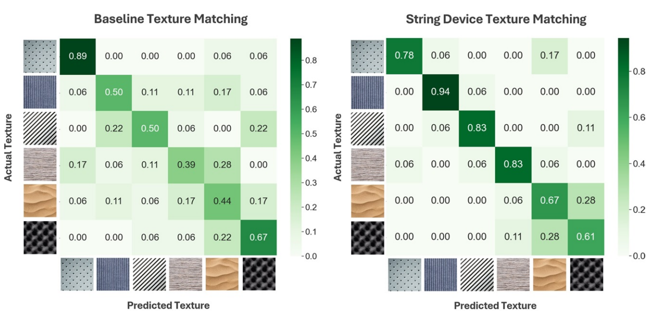


Figure 16: Confusion matrices for the texture matching task for the controller baseline (left) and Reel Feel device (right).

one participant incurring an error on the baseline for the middle two stiffness cubes.

Overall, these results confirm the ability of our system to render objects of different compliances well. Reel Feel performed slightly better than the baseline vibrotactile controller, confirming RQ3, however the difference was small. For a more meaningful comparison, we refer back to the results of the per-category questionnaire in Study 1. Here compliance scored on average 2.1 points better for realism and 2.6 points better for immersion compared to the baseline vibrotactile controller. These results show that although the controller’s "emulation" of compliance using vibrations allowed users to complete the ordering task, vibrations only were not immersive and did not feel like real soft and hard objects in the way Reel Feel did.

6.2.2 Texture Matching Task. Compared to the compliance task, participants found the texture matching task more challenging. For the vibrotactile controller baseline, participants only achieved a mediocre mean accuracy of 56.6% (STD=18.7%). With our Reel Feel system, participants did noticeably better and achieved a mean accuracy of 76.6% (STD=14.0%). Importantly, when switching from the baseline to Reel Feel, participants on average improved by 20.0%. This positive result confirms RQ4.

With Reel Feel, participants did the best for the high-frequency "bumpy" textures including *corduroy*, *metal grating*, and *wood grain*. Notably, these were also the worst performing textures for the baseline device. On the other hand, Reel Feel had the weakest

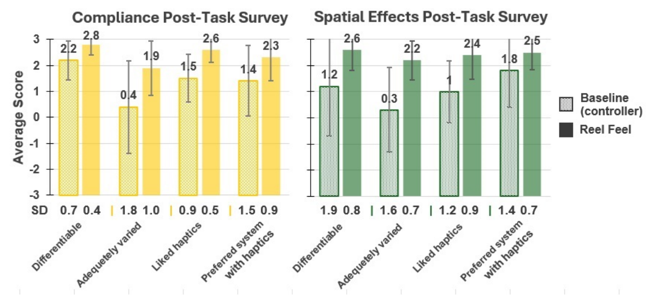


Figure 17: Mean Likert scores for the post-task questionnaire asked after each Study 2 task. Questions were drawn from the questionnaire from Shen et al. [64]. Scores for the fourth question ("I would prefer the system without haptic feedback") were inverted. Error bars are standard deviation.

performance in the the lower-frequency "wavy" textures, including *sand* and *foam*, often confusing them for each other. This behavior also occurred with the baseline, and despite the confusion, Reel Feel still performed better for both on average.

Observing our participants’ behavior during the task, we found most users preferred exploring textures with fast sweeping motions. This may partially explain the performance breakdown for "bumpy" and "wavy" textures. Referencing the grayscale textures images in Figure 12, when using a fast swipe, bumpy textures feel distinct depending on the direction and spacing of bumps. On the other hand, when moving fast over the "wavy" textures in the same direction, both feel similar. Participants who slowed down and used the continuous force feedback of Reel Feel to explore the gray areas of the images between waves tended to do better.

Overall, the results of the texture matching task show that Reel Feel provided a significant improvement in discerning different spatial effects using haptic feedback. In addition, when examining results of the per-category questionnaire from Study 1, users also rated the greatest score improvement of all haptic categories for realism (+111%) and immersion (+75%) when moving from the controller baseline to Reel Feel. This highlights that not only did Reel Feel make virtual textures easier to tell apart and match, but did so by making them feel more realistic and immersive.

6.2.3 Post-Task Questionnaire. As an additional component of this study, we had participants answer a short verbal questionnaire. The goal of this questionnaire was to understand for each task how differentiable the sensations were, whether they adequately varied, how much they liked the haptics, and finally how much they preferred the system’s haptics compared to none at all. Our second goal was to measure the effect that Reel Feel had on the questions compared to the controller baseline.

Results for the questionnaire are shown in Figure 17. We again ran a Wilcoxon test to see if the positive effect of Reel Feel on survey questions was significant. All questions were statistically significant ($W = 0$, $p < 0.01$) except for *differentiable* ($n = 7$, $W = 3.5$, $p > 0.05$) and *adequately varied* ($n = 8$, $W = 7.5$, $p > 0.05$) questions for compliance and the *preferred without* ($n = 6$, $W = 4$, $p > 0.05$) question for spatial effects which were all not significant.

Analyzing the Reel Feel device results, we see that the differentiable and likeable measures scored higher for compliance (mean 2.70, STD=0.46) than spatial effects (mean 2.5, STD=0.87), however the controller baseline also scored decent for compliance (mean 1.85, STD=0.91). This means that although Reel Feel haptics were more differentiable and likable for compliance, the improvement over the controller baseline was greater for spatial effects. Looking back at the test accuracies, this is not surprising. In the tests, participants also performed better in compliance for both the controller baseline and Reel Feel, and the gap between the two was larger for spatial effects.

In sum, the results of this questionnaire are positive. For compliance, participants rated a mean score of 2.40 (STD=0.83) and for spatial effects a mean score of 2.43 (STD=0.80), showing they liked and preferred having the Reel Feel haptics and felt the varied sensations made objects more differentiable. Comparing Reel Feel results between compliance and spatial effects, we also observed participants liked compliance haptics more and found them more differentiable, but less adequately varied. In fact, *adequately varied* for compliance was the lowest-rated question. This was an interesting finding and we believe may be due to the fact that compliance effects felt more recognizably differentiable (between hard and soft), but compared to spatial textures, the haptic forces had far less variations.

6.3 General Discussion

To conclude this section, we share general findings that arose from participant feedback during the studies. First, we believe user expectations had an effect on how well the haptic sensations were received. For example, demos with high-frequency vibrations or large surface geometries were rated better than those with low-frequency vibrations or intricate surface features since users had higher expectations for the sensations to align with what they saw in VR (P5, P7, P9, P10). Second, users reported that sound effects increased the realism of sensations, and helped ease the burden of aligning sensations with visual movements (P3, P6). This matches with the well-known phenomena of audio-haptic and visuo-haptic illusions which can bridge gaps in perception. Third, since the effect of our system's forces weakens the more they point away from the body, demos that aligned their forces with the arm felt better (P2, P7, P9). This is a limitation, which we discuss in the next section. Fourth and finally, users found Reel Feel to be more fun, enjoyable, and immersive when paired with gamified demos such as those in the impulsive forces category (P1, P6). We believe gamified demos improved the Reel Feel experience because users had something to focus on to frame the sensation they were feeling.

7 Limitations & Future Work

While Reel Feel enabled many new types of sensations compared to comparable systems in a compact and wearable form factor, there were nevertheless some tradeoffs made in its design.

First, compared to other wearable haptic techniques, particularly those that arrest the hand using electrical brakes, Reel Feel consumes more more power (~1 W) and is slightly heavier (710 g, albeit on the shoulder). This tradeoff has long existed in the haptics literature as a price to pay for using motors that can render much stronger active forces. Power consumption and user comfort are factors we have considered throughout our design and there is certainly room for improvement (some users suggested more cushioning). However, studies have shown sessions with VR headsets should not exceed 70 minutes to avoid negative VR-induced symptoms [45], thus our goalposts need not necessarily be all-day battery life and wearability.

Second, the maximum feedback force we can render (28.5 N) is limited by the torque of our motors. If a user exerts more force than the motors can provide, it will cause the reels to unspool. In practice, this is not as common or serious as it seems because a user must push aggressively hard. It also becomes harder to overcome the more fingers are actuated as the arm force only occurs once, not for each finger.

To increase rendered force, larger gimbal motors could be used that can output 10-20x the torque, trading off for size and weight. A second solution would be to integrate an actuated arresting gear for our wire spools, similar to Wireality's technique [25]. This would give our system the best of both worlds by rendering pulling forces and allowing the user to feel their own human-scale forces by physically locking the strings.

Finally, our system best renders forces that are parallel to a ray that can be drawn back to the shoulder (i.e., along the cable). For the best experience, VR designers would want to craft interactions that stay near this ray. Forces deviating from the ray, like on the sides of objects, are less physically accurate, but are still convincing up to 45 degree misalignment. The "magic" of visuo-haptic fusion provides a lot of latitude, as noted in much prior work [2]. Hand exoskeletons, like DextrES and HaptX [32, 81], are an obvious comparison that can render such shear forces. This advantage cannot be denied, but we emphasize that we render whole arm kinesthetic feedback that exoskeletons cannot (e.g. catching a baseball). To render both types of feedback, the systems could be used together.

8 Conclusion

In this paper, we presented our work on Reel Feel, a shoulder-mounted haptic device for rendering continuous forces in VR using a series of motorized string spools attached to the fingers. Compared to prior wearable cable systems, our use of motorized spools enables more haptic categories and more fluid rendering. In total, our system was able to render five categories of sensations including rigid geometry, haptic animations, impulsive forces, compliance, and spatial effects. Moreover, these sensations can be combined to create complex haptic effects. All of this was enabled by a compact and wearable prototype device that supported mobile use. In our user studies, participants strongly rated the system in all five measures of immersive, realistic, harmonious, purposeful, and expressive and our system rated on average 42.2% better for these measures compared to a conventional, vibrotactile controller baseline. Users were also able to successfully complete tasks to discern different sensations of compliance and spatial effects. Overall, Reel Feel expands the repertoire of haptic sensations available in one, practical device like no comparable system, and in doing so, improves accessibility to diverse and dynamic XR haptic experiences.

References

[1] Diar Abdlkarim, Massimiliano Di Luca, Poppy Aves, Mohamed Maaroufi, Sang-Hoon Yeo, R. Chris Miall, Peter Holland, and Joeseph M. Galea. 2024. A methodological framework to assess the accuracy of virtual reality hand-tracking systems: A case study with the Meta Quest 2. *Behavior Research Methods* 56, 2 (Feb. 2024), 1052–1063. doi:10.3758/s13428-022-02051-8

[2] Parastoo Abtahi and Sean Follmer. 2018. Visuo-Haptic Illusions for Improving the Perceived Performance of Shape Displays. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–13. doi:10.1145/3173574.3173724

[3] Alexander Achberger, Pirathipan Arulrajah, Michael Sedlmair, and Kresimir Vidackovic. 2022. STROE: An Ungrounded String-Based Weight Simulation Device. In *2022 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. 112–120. doi:10.1109/VR51125.2022.00029

[4] Alexander Achberger, Fabian Aust, Daniel Pohlandt, Kresimir Vidackovic, and Michael Sedlmair. 2021. STRIVE: String-Based Force Feedback for Automotive Engineering. In *The 34th Annual ACM Symposium on User Interface Software and Technology*. ACM, Virtual Event USA, 841–853. doi:10.1145/3472749.3474790

[5] Merwan Achibet, Adrien Girard, Anthony Talvas, Maud Marchal, and Anatole Lecuyer. 2015. Elastic-Arm: Human-scale passive haptic feedback for augmenting interaction and perception in virtual environments. *2015 IEEE Virtual Reality (VR)* (March 2015), 63–68. doi:10.1109/VR.2015.7223325 Conference Name: 2015 IEEE Virtual Reality (VR) ISBN: 9781479917273 Place: Arles, Camargue, Provence, France Publisher: IEEE.

[6] Adilzhan Adilkhanov, Matteo Rubagotti, and Zhanat Kappassov. 2022. Haptic Devices: Wearability-Based Taxonomy and Literature Review. *IEEE Access* 10 (2022), 91923–91947. doi:10.1109/ACCESS.2022.3202986

[7] Karan Ahuja, Vivian Shen, Cathy Mengying Fang, Nathan Riopelle, Andy Kong, and Chris Harrison. 2022. ControllerPose: Inside-Out Body Capture with VR Controller Cameras. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA,) *(CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 108, 13 pages. doi:10.1145/3491102.3502105

[8] Manuel Aiple and André Schiele. 2013. Pushing the limits of the CyberGrasp for haptic rendering. In *2013 IEEE International Conference on Robotics and Automation*. 3541–3546. doi:10.1109/ICRA.2013.6631073 arXiv:1605.05120 [cs].

[9] P. Arcara, L. Di Stefano, S. Mattoccia, C. Melchiorri, and G. Vassura. 2000. Perception of depth information by means of a wire-actuated haptic interface. In *Proceedings 2000 ICRA. Millennium Conference. IEEE International Conference on Robotics and Automation. Symposia Proceedings (Cat. No.00CH37065)*, Vol. 4. 3443–3448 vol.4. doi:10.1109/ROBOT.2000.845258 ISSN: 1050-4729.

[10] K. M. Arafat Aziz, Hu Luo, Lehiany Asma, Weiliang Xu, Yuru Zhang, and Dangxiao Wang. 2020. Haptic Handshank – A Handheld Multimodal Haptic Feedback Controller for Virtual Reality. In *2020 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. IEEE, Porto de Galinhas, Brazil, 239–250. doi:10.1109/ISMAR50242.2020.00047

[11] Hrvoje Benko, Christian Holz, Mike Sinclair, and Eyal Ofek. 2016. NormalTouch and TextureTouch: High-fidelity 3D Haptic Shape Rendering on Handheld Virtual Reality Controllers. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*. ACM, Tokyo Japan, 717–728. doi:10.1145/2984511.2984526

[12] Sliman BensmaÏa, Mark Hollins, and Jeffrey Yau. 2005. Vibrotactile intensity and frequency information in the Pacinian system: A psychophysical model. *Perception & Psychophysics* 67, 5 (July 2005), 828–841. doi:10.3758/BF03193536

[13] Sliman Bensmaïa and Mark Hollins. 2005. Pacinian representations of fine surface texture. *Perception & Psychophysics* 67, 5 (July 2005), 842–854. doi:10.3758/BF03193537

[14] C. Bonivento, A. Eusebi, C. Melchiorri, M. Montanari, and G. Vassura. 1997. WireMan: a portable wire manipulator for touch-rendering of bas-relief virtual surfaces. In *1997 8th International Conference on Advanced Robotics. Proceedings. ICAR'97*. 13–18. doi:10.1109/ICAR.1997.620155

[15] Elodie Bouzbib, Marc Teyssier, Thomas Howard, Claudio Pacchierotti, and Anatole Lécuyer. 2024. PalmEx: Adding Palmar Force-Feedback for 3D Manipulation With Haptic Exoskeleton Gloves. *IEEE Transactions on Visualization and Computer Graphics* 30, 7 (July 2024), 3973–3980. doi:10.1109/TVCG.2023.3244076 Conference Name: IEEE Transactions on Visualization and Computer Graphics.

[16] Yannis Chatzikonstantinou. 2020. Gimbal Motors — Tinymovr documentation. https://tinymovr.readthedocs.io/en/latest/hardware/gimbal.html

[17] Daniel K.Y. Chen, Jean-Baptiste Chossat, and Peter B. Shull. 2019. HaptiVec: Presenting Haptic Feedback Vectors in Handheld Controllers using Embedded Tactile Pin Arrays. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–11. doi:10.1145/3290605.3300401

[18] Po-Yu Chen, Ching-Yi Tsai, Wei-Hsin Wang, Chao-Jung Lai, Chia-An Fan, Shih Chin Lin, Chia-Chen Chi, and Mike Y. Chen. 2023. AirCharge: Amplifying Ungrounded Impact Force by Accumulating Air Propulsion Momentum. In *Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology*. ACM, San Francisco CA USA, 1–11. doi:10.1145/3586183.3606768

[19] Inrak Choi, Heather Culbertson, Mark R. Miller, Alex Olwal, and Sean Follmer. 2017. Grabity: A Wearable Haptic Interface for Simulating Weight and Grasping in Virtual Reality. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology (UIST '17)*. Association for Computing Machinery, New York, NY, USA, 119–130. doi:10.1145/3126594.3126599

[20] Inrak Choi, Elliot W. Hawkes, David L. Christensen, Christopher J. Ploch, and Sean Follmer. 2016. Wolverine: A wearable haptic interface for grasping in virtual reality. In *2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. 986–993. doi:10.1109/IROS.2016.7759169 ISSN: 2153-0866.

[21] Inrak Choi, Eyal Ofek, Hrvoje Benko, Mike Sinclair, and Christian Holz. 2018. CLAW: A Multifunctional Handheld Haptic Controller for Grasping, Touching, and Triggering in Virtual Reality. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–13. doi:10.1145/3173574.3174228

[22] VR Compare. 2020. Quest 2 Controllers: Full Specification. https://vr-compare.com/accessory/quest2controllers

[23] Valve Corporation. 2020. Controllers. https://www.valvesoftware.com/en/index/controllers

[24] CyberGrasp. 2017. CyberGrasp. http://www.cyberglovesystems.com/cybergrasp

[25] Cathy Fang, Yang Zhang, Matthew Dworman, and Chris Harrison. 2020. Wireality: Enabling Complex Tangible Geometries in Virtual Reality with Worn Multi-String Haptics. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems (CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–10. doi:10.1145/3313831.3376470

[26] Cathy Mengying Fang and Chris Harrison. 2021. Retargeted Self-Haptics for Increased Immersion in VR without Instrumentation. In *The 34th Annual ACM Symposium on User Interface Software and Technology* (Virtual Event, USA) *(UIST '21)*. Association for Computing Machinery, New York, NY, USA, 1109–1121. doi:10.1145/3472749.3474810

[27] F. Gemperle, C. Kasabach, J. Stivoric, M. Bauer, and R. Martin. 1998. Design for wearability. In *Digest of Papers. Second International Symposium on Wearable Computers (Cat. No.98EX215)*. 116–122. doi:10.1109/ISWC.1998.729537

[28] Mar Gonzalez-Franco and Tabitha C. Peck. 2018. Avatar Embodiment. Towards a Standardized Questionnaire. *Frontiers in Robotics and AI* 5 (2018). https://www.frontiersin.org/articles/10.3389/frobt.2018.00074

[29] Xiaochi Gu, Yifei Zhang, Weize Sun, Yuanzhe Bian, Dao Zhou, and Per Ola Kristensson. 2016. Dexmo: An Inexpensive and Lightweight Mechanical Exoskeleton for Motion Capture and Force Feedback in VR. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. Association for Computing Machinery, New York, NY, USA, 1991–1995. doi:10.1145/2858036.2858487

[30] Teng Han, Fraser Anderson, Pourang Irani, and Tovi Grossman. 2018. HydroRing: Supporting Mixed Reality Haptics Using Liquid Flow. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology* (Berlin, Germany) *(UIST '18)*. Association for Computing Machinery, New York, NY, USA, 913–925. doi:10.1145/3242587.3242667

[31] Seongkook Heo, Christina Chung, Geehyuk Lee, and Daniel Wigdor. 2018. Thor's Hammer: An Ungrounded Force Feedback Device Utilizing Propeller-Induced Propulsive Force. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. ACM, Montreal QC Canada, 1–11. doi:10.1145/3173574.3174099

[32] Ronan Hinchet, Velko Vechev, Herbert Shea, and Otmar Hilliges. 2018. DextrES: Wearable Haptic Feedback for Grasping in VR via a Thin Form-Factor Electrostatic Brake. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology (UIST '18)*. Association for Computing Machinery, New York, NY, USA, 901–912. doi:10.1145/3242587.3242657

[33] Zhu Hou, Yuru Zhang, and Yi Yang. 2012. Enhancing Touch Screen Games Through a Cable-driven Force Feedback Device. In *2012 International Conference on Virtual Reality and Visualization*. 56–61. doi:10.1109/ICVRV.2012.14

[34] iFlight RC. 2023. GM3506 Gimbal Motor. https://shop.iflight-rc.com/ipower-motor-gm3506-brushless-gimbal-motor-pro967

[35] iFlight RC. 2023. GM5208-24T Gimbal Motor. https://shop.iflight-rc.com/ipower-motor-gm5208-24-brushless-gimbal-motor-pro1347

[36] Anusha Jayasiri, Shuhan Ma, Yihan Qian, Katsuhito Akahane, and Makoto Sato. 2015. Desktop versions of the string-based haptic interface — SPIDAR. In *2015 IEEE Virtual Reality (VR)*. 199–200. doi:10.1109/VR.2015.7223364 ISSN: 2375-5334.

[37] Seungwoo Je, Hyelip Lee, Myung Jin Kim, and Andrea Bianchi. 2018. Windblaster: a wearable propeller-based prototype that provides ungrounded force-feedback. In *ACM SIGGRAPH 2018 Emerging Technologies*. ACM, Vancouver British Columbia Canada, 1–2. doi:10.1145/3214907.3214915

[38] Roland S. Johansson and J. Randall Flanagan. 2009. Coding and use of tactile signals from the fingertips in object manipulation tasks. *Nature Reviews Neuroscience* 10, 5 (May 2009), 345–359. doi:10.1038/nrn2621 Publisher: Nature Publishing Group.

[39] H. Kajimoto, N. Kawakami, S. Tachi, and M. Inami. 2004. SmartTouch: electric skin to touch the untouchable. *IEEE Computer Graphics and Applications* 24, 1 (2004), 36–43. doi:10.1109/MCG.2004.1255807

[40] 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*. ACM, Honolulu HI USA, 1–13. doi:10.1145/3313831.3376280

[41] Hwan Kim, HyeonBeom Yi, Hyein Lee, and Woohun Lee. 2018. HapCube: A Wearable Tactile Device to Provide Tangential and Normal Pseudo-Force Feedback on a Fingertip. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. ACM, Montreal QC Canada, 1–13. doi:10.1145/3173574.3174075

[42] Seahak Kim, Masahiro Ishii, Yasuharu Koike, and Makoto Sato. 2000. Development of Tension Based Haptic Interface and Possibility of Its Application to Virtual Reality. In *Proceedings of the ACM Symposium on Virtual Reality Software and Technology* (Seoul, Korea) *(VRST '00)*. Association for Computing Machinery, New York, NY, USA, 199–205. doi:10.1145/502390.502428

[43] Seung-Chan Kim, Chong-Hui Kim, Gi-Hun Yang, Tae-Heon Yang, Byung-Kil Han, Sung-Chul Kang, and Dong-Soo Kwon. 2009. Small and lightweight tactile display(SaLT) and its application. In *World Haptics 2009 - Third Joint EuroHaptics conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*. IEEE, Salt Lake City, UT, USA, 69–74. doi:10.1109/WHC.2009.4810820

[44] Roberta L. Klatzky, Dianne Pawluk, and Angelika Peer. 2013. Haptic Perception of Material Properties and Implications for Applications. *Proc. IEEE* 101, 9 (Sept. 2013), 2081–2092. doi:10.1109/JPROC.2013.2248691 Conference Name: Proceedings of the IEEE.

[45] Panagiotis Kourtesis, Simona Collina, Leonidas A. A. Doumas, and Sarah E. MacPherson. 2019. Validation of the Virtual Reality Neuroscience Questionnaire: Maximum Duration of Immersive Virtual Reality Sessions Without the Presence of Pertinent Adverse Symptomatology. *Frontiers in Human Neuroscience* 13 (2019). https://www.frontiersin.org/articles/10.3389/fnhum.2019.00417

[46] Robert Kovacs, Eyal Ofek, Mar Gonzalez Franco, Alexa Fay Siu, Sebastian Marwecki, Christian Holz, and Mike Sinclair. 2020. Haptic PIVOT: On-Demand Handhelds in VR. In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology*. ACM, Virtual Event USA, 1046–1059. doi:10.1145/3379337.3415854

[47] Susan J. Lederman. 1974. Tactile roughness of grooved surfaces: The touching process and effects of macro- and microsurface structure. *Perception & Psychophysics* 16, 2 (March 1974), 385–395. doi:10.3758/BF03203958

[48] Jaeyeon Lee, Mike Sinclair, Mar Gonzalez-Franco, Eyal Ofek, and Christian Holz. 2019. TORC: A Virtual Reality Controller for In-Hand High-Dexterity Finger Interaction. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–13. doi:10.1145/3290605.3300301

[49] Lanhai Liu, Satoshi Miyake, Katsuhito Akahane, and Makoto Sato. 2013. Development of string-based multi-finger haptic interface SPIDAR-MF. In *2013 23rd International Conference on Artificial Reality and Telexistence (ICAT)*. 67–71. doi:10.1109/ICAT.2013.6728908

[50] Lanhai Liu, Satoshi Miyake, Katsuhito Akahane, and Makoto Sato. 2013. Development of string-based multi-finger haptic interface SPIDAR-MF. In *2013 23rd International Conference on Artificial Reality and Telexistence (ICAT)*. 67–71. doi:10.1109/ICAT.2013.6728908

[51] Lanhai Liu, Satoshi Miyake, Naoki Maruyama, Katsuhito Akahane, and Makoto Sato. 2014. Development of Two-Handed Multi-finger Haptic Interface SPIDAR-10. In *Haptics: Neuroscience, Devices, Modeling, and Applications (Lecture Notes in Computer Science)*, Malika Auvray and Christian Duriez (Eds.). Springer, Berlin, Heidelberg, 176–183. doi:10.1007/978-3-662-44196-1_22

[52] Pedro Lopes, Sijing You, Lung-Pan Cheng, Sebastian Marwecki, and Patrick Baudisch. 2017. Providing Haptics to Walls & Heavy Objects in Virtual Reality by Means of Electrical Muscle Stimulation. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17)*. Association for Computing Machinery, New York, NY, USA, 1471–1482. doi:10.1145/3025453.3025600

[53] Zhou MA and Pinhas Ben-Tzvi. 2015. RML Glove—An Exoskeleton Glove Mechanism With Haptics Feedback. *IEEE/ASME Transactions on Mechatronics* 20, 2 (April 2015), 641–652. doi:10.1109/TMECH.2014.2305842 Conference Name: IEEE/ASME Transactions on Mechatronics.

[54] Meta. 2022. Meta Quest 2 Controllers | Meta Quest. https://www.meta.com/quest/accessories/quest-2-controllers/

[55] Meta. 2023. All Hands on Deck: Crank up Hand Responsiveness and Unlock New Gameplay with Hands 2.2. https://developer.oculus.com/blog/hand-tracking-22-response-time-meta-quest-developers/

[56] Jun Murayama, Laroussi Bougrila, YanLin Luo, Katsuhito Akahane, Shoichi Hasegawa, Beat Hirsbrunner, and Makoto Sato. 2004. SPIDAR G&G: A Two-Handed Haptic Interface for Bimanual VR Interaction. (2004).

[57] Kazuki Nagai, Soma Tanoue, Katsuhito Akahane, and Makoto Sato. 2015. Wearable 6-DoF wrist haptic device "SPIDAR-W". In *SIGGRAPH Asia 2015 Haptic Media And Contents Design*. ACM, Kobe Japan, 1–2. doi:10.1145/2818384.2818403

[58] Evan Pezent, Ali Israr, Majed Samad, Shea Robinson, Priyanshu Agarwal, Hrvoje Benko, and Nick Colonnese. 2019. Tasbi: Multisensory Squeeze and Vibrotactile Wrist Haptics for Augmented and Virtual Reality. In *2019 IEEE World Haptics Conference (WHC)*. 1–6. doi:10.1109/WHC.2019.8816098

[59] PowerStream. 2013. Introduction of INR18650-25R. https://www.powerstream.com/p/INR18650-25R-datasheet.pdf

[60] Pornthep Preechayasomboon, Ali Israr, and Majed Samad. 2020. Chasm: A Screw Based Expressive Compact Haptic Actuator. 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:10.1145/3313831.3376512

[61] Renesas. 2023. What are Brushless DC Motors. https://www.renesas.com/us/en/support/engineer-school/brushless-dc-motor-01-overview

[62] Grégoire Richard, Thomas Pietrzak, Ferran Argelaguet, Anatole Lécuyer, and Géry Casiez. 2023. MultiVibes: What if your VR Controller had 10 Times more Vibrotactile Actuators?. In *2023 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. IEEE, Sydney, Australia, 703–712. doi:10.1109/ISMAR59233.2023.00085

[63] Suji Sathiyamurthy, Melody Lui, Erin Kim, and Oliver Schneider. 2021. Measuring Haptic Experience: Elaborating the HX model with scale development. In *2021 IEEE World Haptics Conference (WHC)*. 979–984. doi:10.1109/WHC49131.2021.9517220

[64] Vivian Shen, Tucker Rae-Grant, Joe Mullenbach, Chris Harrison, and Craig Shultz. 2023. Fluid Reality: High-Resolution, Untethered Haptic Gloves using Electroosmotic Pump Arrays. In *Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology* (, San Francisco, CA, USA,) *(UIST '23)*. Association for Computing Machinery, New York, NY, USA, Article 8, 20 pages. doi:10.1145/3586183.3606771

[65] Vivian Shen, Craig Shultz, and Chris Harrison. 2022. Mouth Haptics in VR Using a Headset Ultrasound Phased Array. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 275, 14 pages. doi:10.1145/3491102.3501960

[66] Bo Sheng, Jianyu Zhao, Yanxin Zhang, Shengquan Xie, and Jing Tao. 2023. Commercial device-based hand rehabilitation systems for stroke patients: State of the art and future prospects. *Heliyon* 9, 3 (Feb. 2023), e13588. doi:10.1016/j.heliyon.2023.e13588

[67] SimpleFOC. 2022. Simple Field Oriented Control (FOC) project. https://docs.simplefoc.com

[68] Bukun Son and Jaeyoung Park. 2018. Haptic Feedback to the Palm and Fingers for Improved Tactile Perception of Large Objects. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology (UIST '18)*. Association for Computing Machinery, New York, NY, USA, 757–763. doi:10.1145/3242587.3242656

[69] Anthony Steed, Sebastian Friston, Vijay Pawar, and David Swapp. 2020. Docking Haptics: Extending the Reach of Haptics by Dynamic Combinations of Grounded and Worn Devices. In *Proceedings of the 26th ACM Symposium on Virtual Reality Software and Technology (VRST '20)*. Association for Computing Machinery, New York, NY, USA, 1–11. doi:10.1145/3385956.3418943

[70] Paul Strohmeier and Kasper Hornbæk. 2017. Generating Haptic Textures with a Vibrotactile Actuator. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17)*. Association for Computing Machinery, New York, NY, USA, 4994–5005. doi:10.1145/3025453.3025812

[71] Yuning Su, Weizhi Nai, Xiaoying Sun, and Zuowei Sun. 2021. Design and Modeling of an Ungrounded Haptic Gun that Simulates Recoil Using Asymmetric Force. In *2021 IEEE World Haptics Conference (WHC)*. IEEE, Montreal, QC, Canada, 361–366. doi:10.1109/WHC49131.2021.9517202

[72] Yudai Tanaka, Jacob Serfaty, and Pedro Lopes. 2024. Haptic Source-Effector: Full-Body Haptics via Non-Invasive Brain Stimulation. 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:10.1145/3613904.3642483

[73] Yudai Tanaka, Alan Shen, Andy Kong, and Pedro Lopes. 2023. Full-hand Electro-Tactile Feedback without Obstructing Palmar Side of Hand. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems* (Hamburg, Germany) *(CHI '23)*. Association for Computing Machinery, New York, NY, USA, Article 80, 15 pages. doi:10.1145/3544548.3581382

[74] Yujie Tao, Shan-Yuan Teng, and Pedro Lopes. 2021. Altering Perceived Softness of Real Rigid Objects by Restricting Fingerpad Deformation. In *The 34th Annual ACM Symposium on User Interface Software and Technology*. ACM, Virtual Event USA, 985–996. doi:10.1145/3472749.3474800

[75] Fong Wee Teck, Huang Zhiyong, Farzam Farbiz, Cher Jingting, Chin Ching Ling, and Susanto Rahardja. 2011. Ungrounded handheld device for simulating high-forces of ball impacts in virtual tennis. In *SIGGRAPH Asia 2011 Emerging Technologies*. ACM, Hong Kong China, 1–1. doi:10.1145/2073370.2073389

[76] Shan-Yuan Teng, Tzu-Sheng Kuo, Chi Wang, Chi-huan Chiang, Da-Yuan Huang, Liwei Chan, and Bing-Yu Chen. 2018. PuPoP: Pop-up Prop on Palm for Virtual Reality. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology (UIST '18)*. Association for Computing Machinery, New York, NY, USA, 5–17. doi:10.1145/3242587.3242628

[77] TMotor. 2023. GB2208 Gimbal Type Motors. https://store.tmotor.com/goods-447-GB2208.html

[78] Ching-Yi Tsai, I-Lun Tsai, Chao-Jung Lai, Derrek Chow, Lauren Wei, Lung-Pan Cheng, and Mike Y. Chen. 2022. AirRacket: Perceptual Design of Ungrounded,

Directional Force Feedback to Improve Virtual Racket Sports Experiences. In *CHI Conference on Human Factors in Computing Systems*. ACM, New Orleans LA USA, 1–15. doi:10.1145/3491102.3502034
[79] Hsin-Ruey Tsai, Jun Rekimoto, and Bing-Yu Chen. 2019. ElasticVR: Providing Multilevel Continuously-Changing Resistive Force and Instant Impact Using Elasticity for VR. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–10. doi:10.1145/3290605.3300450
[80] Dzmitry Tsetserukou, Katsunari Sato, and Susumu Tachi. 2010. ExoInterfaces: novel exosceleton haptic interfaces for virtual reality, augmented sport and rehabilitation. In *Proceedings of the 1st Augmented Human International Conference (AH '10)*. Association for Computing Machinery, New York, NY, USA, 1–6. doi:10.1145/1785455.1785456
[81] Scott Varga. 2022. Haptic Gloves G1 - Gloves for virtual reality and robotics. https://haptx.com/
[82] Chiu-Hsuan Wang, Chen-Yuan Hsieh, Neng-Hao Yu, Andrea Bianchi, and Liwei Chan. 2019. HapticSphere: Physical Support To Enable Precision Touch Interaction in Mobile Mixed-Reality. *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)* (March 2019), 331–339. doi:10.1109/VR.2019.8798255 Conference Name: 2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR) ISBN: 9781728113777 Place: Osaka, Japan Publisher: IEEE.
[83] Yu-Wei Wang, Yu-Hsin Lin, Pin-Sung Ku, Yōko Miyatake, Yi-Hsuan Mao, Po Yu Chen, Chun-Miao Tseng, and Mike Y. Chen. 2021. JetController: High-speed Ungrounded 3-DoF Force Feedback Controllers using Air Propulsion Jets. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. ACM, Yokohama Japan, 1–12. doi:10.1145/3411764.3445549
[84] Eric Whitmire, Hrvoje Benko, Christian Holz, Eyal Ofek, and Mike Sinclair. 2018. Haptic Revolver: Touch, Shear, Texture, and Shape Rendering on a Reconfigurable Virtual Reality Controller. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–12. doi:10.1145/3173574.3173660
[85] Kyle N. Winfree, Jamie Gewirtz, Thomas Mather, Jonathan Fiene, and Katherine J. Kuchenbecker. 2009. A high fidelity ungrounded torque feedback device: The iTorqU 2.0. In *World Haptics 2009 - Third Joint EuroHaptics conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*. IEEE, Salt Lake City, UT, USA, 261–266. doi:10.1109/WHC.2009.4810866
[86] 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* (Berlin, Germany) *(UIST '18)*. Association for Computing Machinery, New York, NY, USA, 365–378. doi:10.1145/3242587.3242645
[87] Takashi Yoshioka, James C. Craig, Graham C. Beck, and Steven S. Hsiao. 2011. Perceptual Constancy of Texture Roughness in the Tactile System. *Journal of Neuroscience* 31, 48 (Nov. 2011), 17603–17611. doi:10.1523/JNEUROSCI.3907-11.2011 Publisher: Society for Neuroscience Section: Articles.
[88] Eric M. Young, Amirhossein H. Memar, Priyanshu Agarwal, and Nick Colonnese. 2019. Bellowband: A Pneumatic Wristband for Delivering Local Pressure and Vibration. In *2019 IEEE World Haptics Conference (WHC)*. IEEE, Tokyo, Japan, 55–60. doi:10.1109/WHC.2019.8816075
[89] Andre Zenner and Antonio Kruger. 2017. Shifty: A Weight-Shifting Dynamic Passive Haptic Proxy to Enhance Object Perception in Virtual Reality. *IEEE Transactions on Visualization and Computer Graphics* 23, 4 (April 2017), 1285–1294. doi:10.1109/TVCG.2017.2656978
[90] Zhong-Yi Zhang, Hong-Xian Chen, Shih-Hao Wang, and Hsin-Ruey Tsai. 2022. ELAXO : Rendering Versatile Resistive Force Feedback for Fingers Grasping and Twisting. In *Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology (UIST '22)*. Association for Computing Machinery, New York, NY, USA, 1–14. doi:10.1145/3526113.3545677

A HX Questionnaire Questions

These questions were drawn from the HX model from Sathiyamurthy et al. [63] and are presented in the same order.

- **H2** I like having the haptic feedback as part of the experience
- **A2** I like how the haptic feedback itself feels, regardless of its role in the system
- **A3** I disliked the haptic feedback
- **A4** I would prefer the system without the haptic feedback
- **A1** The haptic feedback felt satisfying
- **E2** I felt adequate variations in the haptic feedback
- **E4** The haptic feedback changes depending on how things change in the scene
- **E5** The haptic feedback reflects varying inputs and events
- **E1** The haptic feedback all felt the same
- **I4** The haptic feedback increased my involvement in the task
- **I3** The haptic feedback helped me focus on the task
- **E3** The haptic feedback helps me distinguish what was going on
- **I2** I felt engaged with the system due to the haptic feedback
- **H1** The haptic feedback fits well with the other senses
- **R1** The haptic feedback was realistic
- **R2** The haptic feedback was believable
- **R3** The haptic feedback was convincing
- **R4** The haptic feedback matched my expectation
- **H3** The haptic feedback felt disconnected from the rest of the experience
- **H5** The haptic feedback felt out of place
- **I1** The haptic feedback distracted me from the task
- **H4** The haptic feedback felt appropriate when and where I felt it

A Complete Questionnaire Results

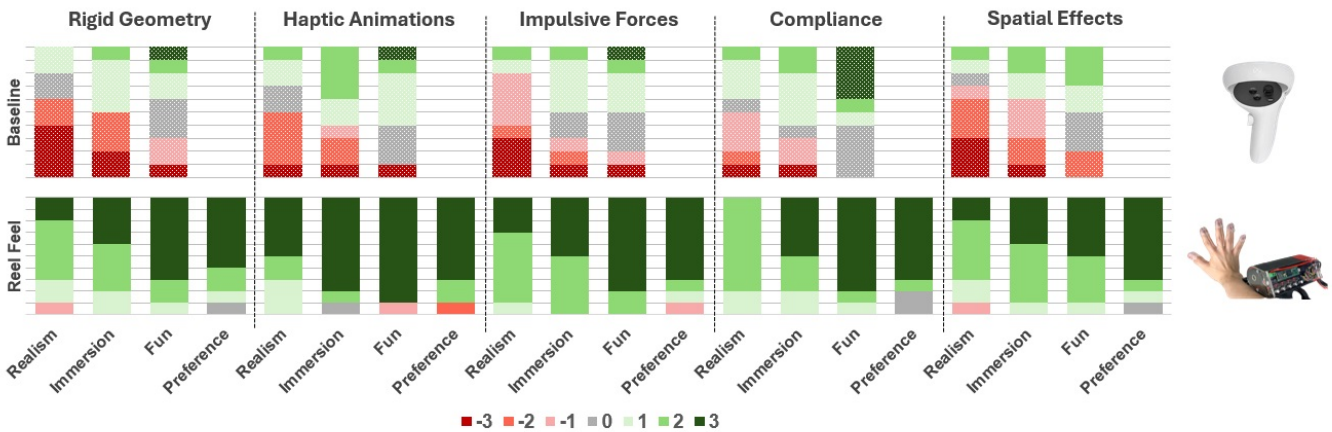


Figure 18: Full participant responses (-3 to +3) of the category-specific questionnaire from Study 1.

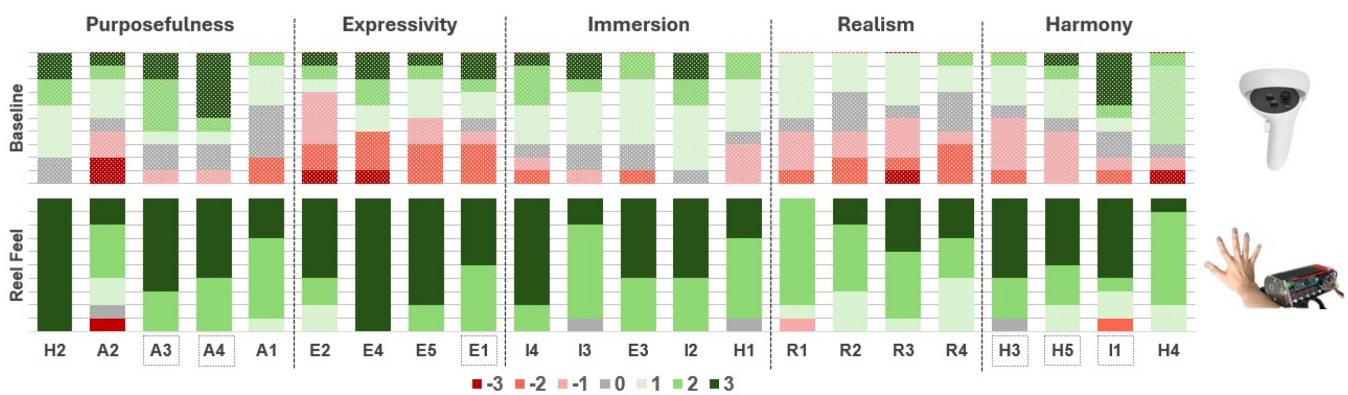


Figure 19: Full participant responses (-3 to +3) of the pan-category questionnaire from Study 1. Scores for negative questions (marked with dashed boxes) were inverted.

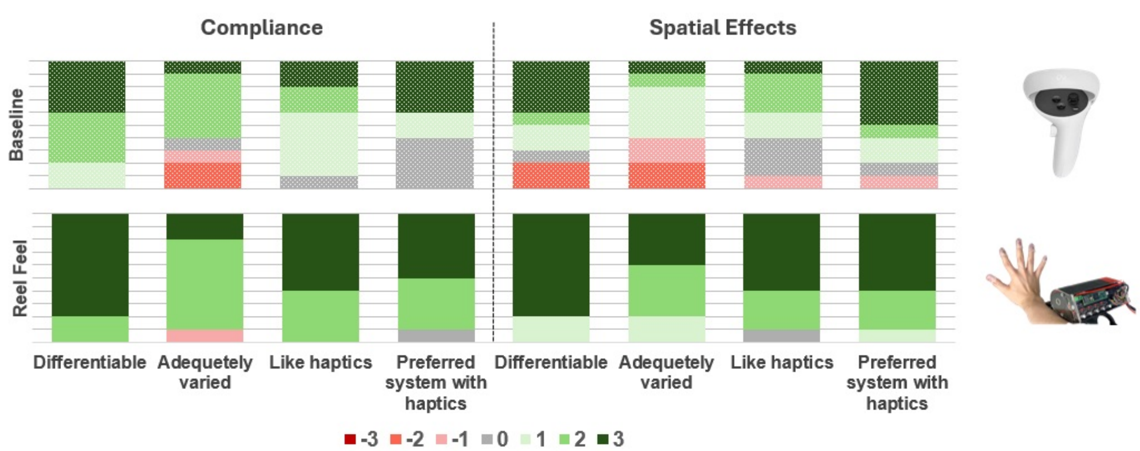


Figure 20: Full participant responses (-3 to +3) of the post-task questionnaire from Study 2.