Grabity: A Wearable Haptic Interface for Simulating Weight and Grasping in Virtual Reality

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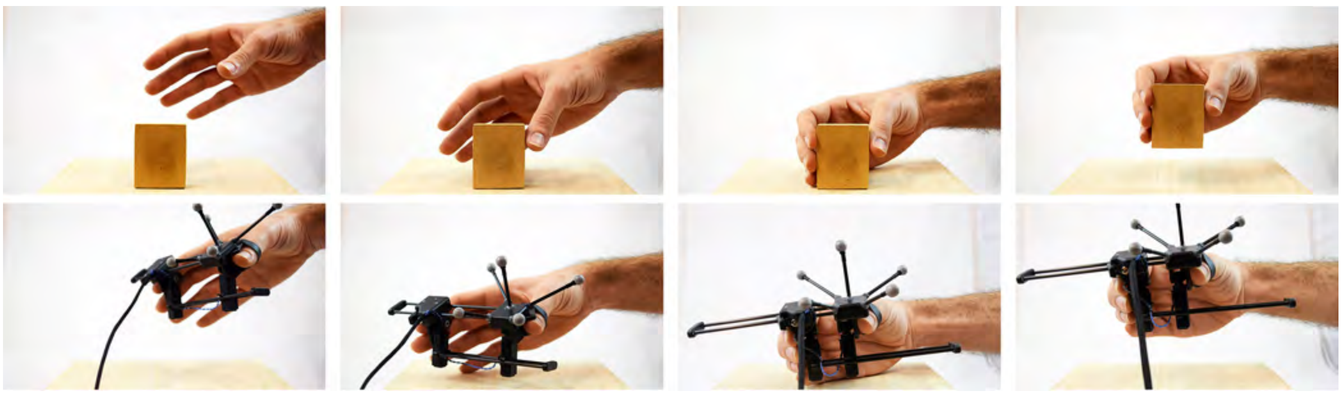

Figure 1. ***Grabity*** **is a novel, unified design based on the combination of vibrotactile feedback, uni-directional brakes, and asymmetric skin stretch. The gripper-style haptic device can simulate grasping motions with a real object (top), in Virtual Reality (bottom). Gravity provides vibrotactile feedback during contact, high stiffness force feedback during grasping, and weight force feedback during lifting.**

ABSTRACT

Ungrounded haptic devices for virtual reality (VR) applications lack the ability to convincingly render the sensations of a grasped virtual object's rigidity and weight. We present *Grabity*, a wearable haptic device designed to simulate kinesthetic pad opposition grip forces and weight for grasping virtual objects in VR. The device is mounted on the index finger and thumb and enables precision grasps with a wide range of motion. A unidirectional brake creates rigid grasping force feedback. Two voice coil actuators create virtual force tangential to each finger pad through asymmetric skin deformation. These forces can be perceived as gravitational and inertial forces of virtual objects. The rotational orientation of the voice coil actuators is passively aligned with the real direction of gravity through a revolute joint, causing the virtual forces to always point downward. This paper evaluates the performance of Grabity through two user studies, finding promising ability to simulate different levels of weight with convincing object rigidity. The first user study shows that Grabity can convey various magnitudes of weight and force sensations to users by manipulating the amplitude of the asymmetric vibration. The second user study shows that users can differentiate different weights in a virtual environment using Grabity.

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INTRODUCTION

In order to grasp and manipulate objects in the real world, humans rely on haptic cues such as fingertip contact pressure and kinesthetic feedback of finger positions to determine shape, and proprioceptive and cutaneous feedback for weight perception, among other modalities [26]. To create haptic interfaces that can provide a realistic grasping experience we must support these same modalities and render similar forces to a user's hands. Current virtual reality (VR) systems can render realistic 3D objects visually, but most lack the ability to provide a realistic haptic experience. Grounded kinesthetic haptic devices can render many of these forces for either a single contact point [27] or even five fingers [14]. However, grounded haptic devices are large, mechanically complex, and have limited workspaces.

In the context of consumer VR, haptic devices must become more compact and mobile. However, it remains challenging to render forces, such as grasp and weight, using ungrounded haptic feedback devices. A variety of wearable and portable haptic devices have been investigated with different types of gloves, exoskeletons, and handheld controllers to provide an immersive experience to users during interaction in VR. While these devices provide haptic feedback for informational cues, 3D shape information, and stiffness of virtual objects, creating kinesthetic feedback, such as weight and inertia of virtual objects, still remains a challenge. This challenge comes from the fact that wearable and portable haptic devices are grounded to the user's body, not to the environment. There is no electromechanical structure from which to generate a kinesthetic force outside of the human body. While there are conflicting constraints of mobility and performance, an ideal haptic device would be a compact and lightweight mobile device with the ability to create the necessary forces.

We introduce *Grabity*, a mobile, ungrounded haptic device, which can display various types of kinesthetic feedback to enhance the grasping and manipulating of virtual objects. This feedback includes gravity, force for inertia, as well as rigid stiffness force feedback between opposing fingers. The design combines a "gripper" style haptic device [5, 32], for providing opposing forces between the index finger and thumb, and a skin deformation mechanism for rendering inertia and mass of a virtual object. Previous work has demonstrated that asymmetric skin deformation enabled by linear vibratory motors can generate perceived virtual forces tangential to finger pads [40, 2, 12].

We apply this same principle to render the virtual gravity force of different virtual masses, and their associated inertia in 1 degree of freedom per finger. To create the sensation of gravity and inertia, we adapt two voice coil actuators to a mobile gripper type haptic device. We utilize different magnitudes of asymmetric vibrations to generate various levels of force feedback. The gripper element includes a unidirectional brake to create the rigid, high-stiffness, opposing forces between a finger and thumb.

While previous work has investigated the maximum perceived force of a single asymmetric skin deformation signal [40, 12], we specifically investigate weight perception and the ability to discriminate different levels of stimuli. We conducted a user study with 12 participants to measure the perceived virtual force, which showed that users can discriminate at least two levels of positive and negative force and we characterized their associated magnitude. We then applied these results to a VR environment allowing users to grasp and manipulate virtual objects with contact forces (vibration), pad opposition grip forces (uni-directional braking), gravity and inertia (asymmetric skin deformation). A user evaluation with 5 participants highlighted the ease of manipulation and suggested that users could discriminate 3 levels of virtual weight.

CONTRIBUTIONS

- Design considerations for integrating voice coil actuators into a mobile haptic device for displaying weight and inertia of virtual objects.
- Combining grasp force feedback with asymmetric skin deformation in a virtual environment.
- An integrated VR system with haptic rendering of virtual gravity and inertia, contact forces, and grasp feedback.
- Quantification of perceived virtual forces generated through voice coil actuators, by controlling the magnitude of asymmetric vibrations.
- Verification that Grabity allows users to differentiate between virtual weights in VR.

RELATED WORK

Wearable and Handheld Haptic Devices

In contrast to grounded haptic devices which ground forces externally, wearable and handheld haptic devices ground forces to a user's body. These wearable and handheld devices do not restrict the motion of a user, allowing the user to move around freely in space. Thus, such devices can support a much larger workspace.

Wand-based controllers are often used in VR environments, thus a number of haptics-enabled handheld devices have been investigated. These devices are ungrounded, so they cannot render external forces. They also do not allow users to perceive the shape of objects through enclosure, or to grasp objects naturally. They are, however, more compact and map easily to existing spatial input techniques. Many such devices (e.g., the HTC Vive controller) utilize vibrotactile feedback. NormalTouch and TextureTouch, on the other hand, are devices that can render texture or contact angle to a single finger [7] using a tilt platform and tactile array, respectively. Grasping in handheld devices has also been explored with some systems that provide variable stiffness feedback [16]. A recent wand-based controller gives various kinesthetic haptic feedback by shifting its center of mass [47].

Cutaneous force feedback displays stimulate mechanoreceptors in the skin that enable people to perceive local shape, texture and other features. Researchers have developed wearable fingertip-based devices that render contact forces [29, 34], textures [45] and skin stretch [9, 41]. However these devices cannot provide rigid grasping sensations as there is no force constraining finger motion.

Researchers have also explored glove-style, wearable exoskeletons to provide haptic feedback for grasping of virtual objects. CyberGrasp, a commercial device, grounded force feedback for each finger through a number of pulleys to the wrist [1]. More recently, Dexmo has taken a similar approach, using low cost servo motors and mechanical linkages to provide force feedback for five fingers [15]. While those devices grounded forces to the wrist, the Rutgers Master II renders forces between the fingers and the palm [8]. Other gripper force feedback devices display forces directly between the index finger and thumb, which can be combined with other haptic modalities such as voice-coil actuators for contact and acceleration feedback [23]. Our Wolverine haptic device utilizes uni-directional brakes between three fingers and a thumb to render rigid body forces [10]. While these wearable devices can provide kinesthetic feedback for grasping between fingers, they are unable to render external forces such as gravity.

Skin Stretch Feedback

Skin stretch (lateral or shear forces deforming the skin) can be perceived by different mechanoreceptors and is used in perception of texture, friction, slip, and force [21]. Skin stretch is also believed to be used to aid in grasping and manipulating objects [20]. Cutaneous finger tip based skin stretch displays for texture perception have been investigated by Hayward and collaborators using small (1mm), low displacement, vibrating piezo elements [17, 35]. Skin stretch has also been used to display friction [38].

Skin stretch can be perceived directionally, thus it has also been investigated to provide directional cues for applications such as driving guidance [36]. In addition, while many cutaneous haptic devices focus on finger tip feedback, skin stretch can also be used to display information to arms and other body locations [6, 19].

Skin stretch has also been used to display forces tangentially to finger pads, to simulate gravity [29] or other forces [34, 43]. These devices use physical tactors in contact with the finger pad which are displaced laterally across the finger to stretch it. These tactors can be placed in a pen type end effector to give force feedback and guidance cues [39], in a handheld device to create forces and torques [37], or mounted directly to the finger tip to render both contact force and weight [9, 41]. These devices can create large amounts of perceived skin stretch but rely on relatively large and bulky DC motors.

More recently, asymmetric, vibration based skin stretch has been shown to enable perception of direction and pulling force [40] . This can be enabled by linear vibration actuators, such as piezo or linear resonant actuators, which can be compact and lightweight. Culbertson et al. modeled this behavior for voice coil actuators [12]. In addition to force output, asymmetric skin stretch can be used for wearable directional guidance cues [13]. To our knowledge, asymmetric skin stretch has not yet been investigated in the context of other haptic modalities, such as gripping force feedback.

Haptic Devices for Weight Simulation

Externally grounded haptic devices [27, 31, 14] can render external forces such as gravity. Another approach is to change the mass of the device by moving a fluid to an external reservoir [33]. Researchers also moved the center of mass actively to give similar effects [47]. Other researchers have attempted to use ungrounded, wearable devices to simulate the weight of virtual objects using skin stretch [29, 41]. However these devices utilize larger servo motors. Amemiya and Maeda created a slider-crank system to generate asymmetric vibrations and showed that these vibrations can be used to change the perceived heaviness of an object [3]. However, this system required the user to always keep the device oriented towards gravity and the asymmetric vibrations were created using a bulky mechanical apparatus rather than a vibration actuator as in this paper.

DESIGN CONSIDERATION

Background: Grasping and manipulation

We receive a variety of haptic sensations while we grasp and manipulate an object. Imagine that there is a cup of coffee in front of you. First, you will notice that you made contact when you touch the cup with your fingers. Once you grasp the cup, you will notice its shape and size. Then, as you lift it, you will feel its weight. During this short interaction, a person perceives rich information about the cup through haptic feedback, such as texture, temperature, 3D shape, stiffness, and weight [25].

In this work, we focus on the force feedback (kinesthetic) aspects and do not explore stiffness, texture, or temperature components. Even though we still need more information for fully immersive haptic experience, we believe basic force feedback for touching, grasping, lifting, and shaking can dramatically improve manipulation in current VR interfaces.

Force feedback is necessary for:

- *Touching* to recognize if we reach or are in contact with an object.
- *Grasping* to recognize if we have successfully grasped an object, but also to stabilize our hand motion, and haptically perceive object size.
- *Gravity* to recognize if we lifted the object, but also to feel its weight.
- *Inertia* to recognize if we translate the object too fast.

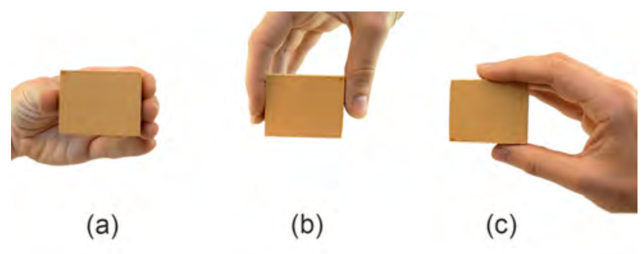

Figure 2. Three directions of pad opposition grasp for holding an object.

Humans sense weight throughout the body [22]. Muscle spindles and golgi tendon organs in human arm sense weights proprioceptively [18]. At the same time, mechanoreceptors on finger pads sense weights by being pressurized or distorted laterally [21]. By combining proprioceptive and tactile (cutaneous) feedback, humans sense weights naturally. However, it would be desirable if we can create weight sensation using just tactile feedback. Haptic systems creating proprioceptive weight sensation are generally bulky and heavy because they need to be grounded externally with multiple linkages. Minamizawa et al. have investigated the role of proprioceptive and tactile (cutaneous) sensation for weight measuring [30]. According to their work, tactile sensation without proprioceptive sensation provides certain perceptive cues that help differentiate weights.

While there are various ways to grasp objects, we have narrowed our focus to pad opposition grasps between index finger, middle finger, and thumb. We believe this grasp choice would be sufficient for basic manipulations, such as picking and placing virtual objects. In addition, research has yet to show that people can simultaneously integrate multiple directions of asymmetric skin stretch well [13]. This also reduces the weight and cost of the device. There are three directions that the object can be held in the pad opposition type grip, as illustrated in Figure 2. We can see that the force direction created by object mass is parallel to the plane of finger pads in Figure 2 (a) and (b). On the other hand, the force direction created by object mass is normal to the finger pads plane in Figure 2 (c). If we utilize cutaneous skin stretch as opposed to pressure or proprioceptive cues, then we cannot render weight in orientation (c).

To design a system which can provide feedback for touching, grasping, gravity, and inertia, we chose to combine a gripper type device with cutaneous asymmetric skin stretch. For this device's performance for our scenarios, we emphasize the optimization of the following design parameters:

- *Weight.* The overall mass of the device should be lightweight in order for the skin stretch to be perceived as weight, as the virtual forces have been shown to be low (< 30g) [40] and weight perception acuity decreases as total weight increases [44].
- *Motion range.* Wide range of motion to grasp and manipulate different sized objects.
- *Mechanical complexity.* Minimize the number of actuators, to reduce cost and weight.
- *Anatomical alignment.* The index finger and thumb should be parallel in alignment to receive consistent directional skins stretch cues. Misalignment can create confusion and unintentional torques.
- *Stiffness.* High stiffness for pad opposition forces. Grip force of the human hand can exceed 100N [4].
- *Performance.* Accurate and fast position tracking to integrate into VR.

IMPLEMENTATION

Overall Structure

As shown in Figure 3, the device is composed of three rigid bodies: a base, a sliding part, and a swinging part. The base is mounted on the thumb, and it has retroreflective markers for an external optical motion capture system for tracking the thumb's position and orientation. The sliding part is mounted on the index finger and is connected with the base through a prismatic joint that is composed of two carbon fiber tubes. This single degree of freedom allows pinching motions for grasping objects. The brake mechanism on the sliding part contains a brake lever, a tendon, and a motor. The swinging part, which is connected to the sliding part and base through revolute joints (bearings), is composed of two voice coil actuators (Haptuator Mark II, Tactile Labs) and a prismatic joint made of carbon fiber tubes. Each voice coil actuator is placed closely to the index finger and thumb pads so that it can transmit the desired vibration signals properly. The offset distance between

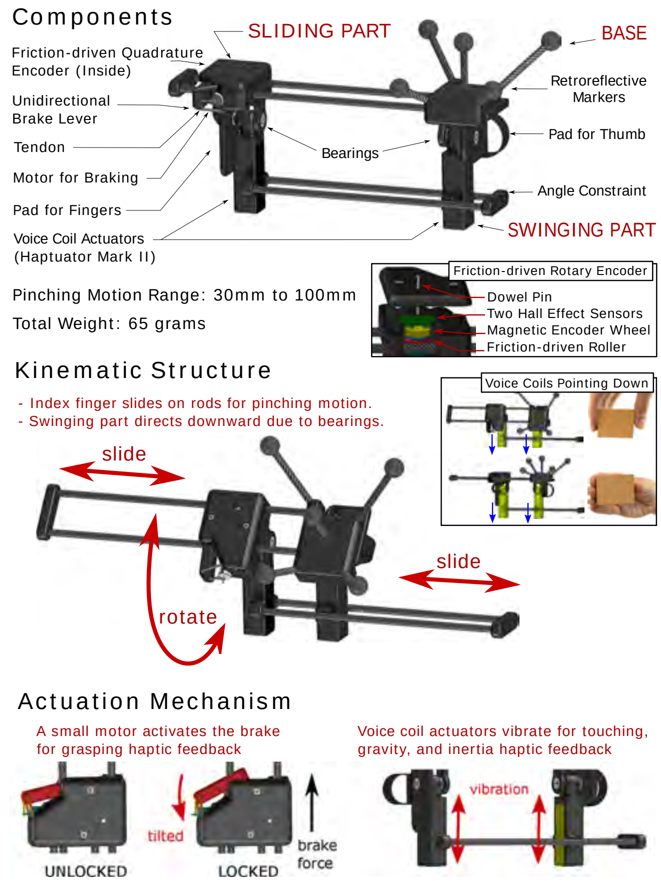

Figure 3. Overall mechanical structure and actuation mechanism.

the revolute joint and center of mass of the swinging part ensures that the direction of the voice coil actuators are always passively directed to be normal to ground. The prismatic joint on the swinging part constrains the two angles of voice coil actuators to be the same while allowing them to slide relative to one another. Most parts of the device are 3D printed using a Formlabs 2 printer (SLA technology), and the device weighs 65 grams.

Actuation for Force Feedback

Grabity contains two types of actuators: a brake mechanism and two voice coil actuators. The brake mechanism is used to create a rigid grasping force, while the voice coil actuators provide both touch sensation at initial contact and the sensation of weight when lifting the object. Figure 4 shows the system diagram of Grabity and Figure 5 shows our custom circuit design for voice coil actuators.

Touching: Conventional Vibration

When a user touches a virtual object without grasping, the voice coil actuators act like conventional vibrotactile transducers and play simple symmetric vibrations to indicate the point of initial contact. Without any haptic feedback it is difficult to detect contact with an object because users rely on visual feedback only. The contact vibration in our system was only played during transient events, not during steady-state con-

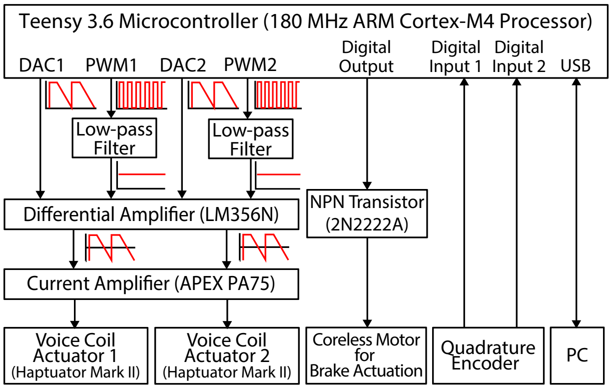

Figure 4. Mechatronic system block diagram.

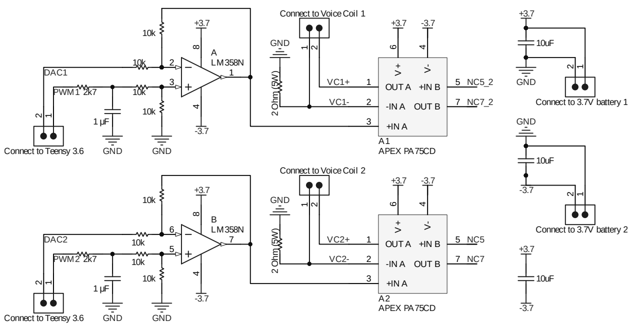

Figure 5. Current-drive circuitry for two voice coil actuators.

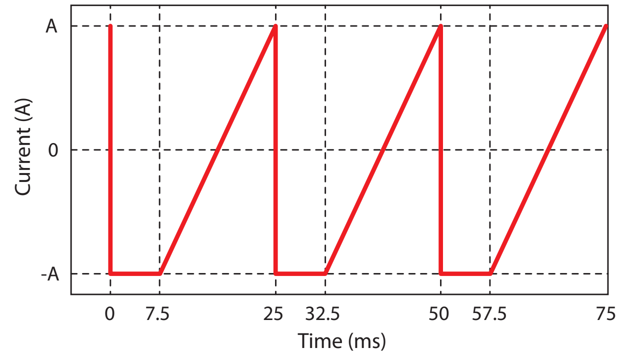

Figure 6. Current signal generating asymmetric vibration. A **is amplitude of current.**

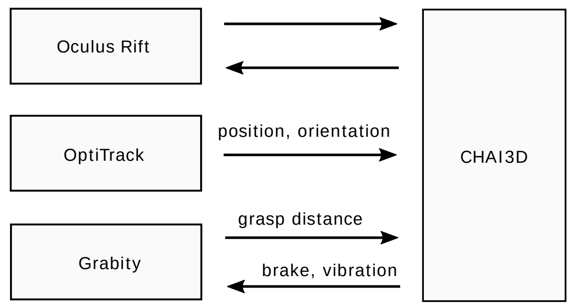

Figure 7. Block diagram of VR application.

tact. VerroTouch [24] showed that playing vibrations during transient events can render realistic contact sensations.

The voice coil actuator on the index finger or the thumb vibrates individually depending on which finger is contacting the virtual object. While only contacting an object, the brake is open so the sliding part floats on the base with some tolerance. Therefore, the vibration interfering the other side of the device is not very perceptible.

Grasping: Unidirectional Brake Mechanism

When a user grasps a virtual object, the brake mechanism is activated to create a rigid passive force. We adapted this unidirectional brake mechanism from our Wolverine system [10]. The brake mechanism provides a locking force using a brake lever, which is activated by a small DC motor (6 mm). Once the brake is engaged, the motor is turned off and the user's own grasping force keeps the brake lever engaged. While the brake is engaged it provides strong resistance that exceeds 100 N in the direction of the two fingers. However, when the user releases their grip, the brake disengages, allowing the user to open her hand. While Wolverine [10] used a rubber tendon to move the brake lever back to the original position when releasing a grip, we use two magnets (one on the brake lever and the other on the body of the device) to reset the lever, for more consistent and reliable performance.

Weight: Asymmetric Vibration

When a user lifts a virtual object, the voice coil actuators vibrate asymmetrically to generate the sensation of weight. If the magnet inside the voice coil actuator moves down quickly and moves up slowly, the skin on the user's finger pads is stretched asymmetrically. As described in section describing Overall Structure and shown in the Kinematic Structure in Figure 3, the passive bearing mechanism orients the voice coils in the direction of gravity, thus we assume the asymmetric vibration is rendered normal to the ground. By changing the asymmetry of the vibration, Grabity simulates various weights.

Figure 6 shows the shape of commanded current pulses. The shape of these current pulses is designed to give the actuators a large step of current initially to cause a large acceleration in the magnet, then to ramp the current back down to slowly return that magnet to its starting position. To achieve this asymmetric actuation, a fast analog signal and current controller are required. Therefore, we used a Teensy 3.6 microcontroller (ARM Cortex-M4 at 180 Mhz with two DACs) generating 15 kHz analog signal output and a linear current-drive circuit. A current-drive circuit creates less effective damping to the system than a voltage-drive circuit, so it is more suitable for asymmetric vibration control [28]. Based on the previous work from Culbertson et al., we chose a drive signal with a 40 Hz frequency (25 ms period) and 0.3 pulse width ratio (t_1 = 7.5 ms and t_2 = 17.5 ms) [12]. To simulate various weight sensations, we change the amplitude A of the signal, while keeping the frequency and pulse width ratio fixed.

Inertia: Asymmetric Vibration + Acceleration Feedback

When a user shakes or moves a virtual object quickly, the two voice coil actuators generate asymmetric vibrations proportional to the acceleration of the user's hand. This feedback control enables Grabity to render inertia of the virtual object.

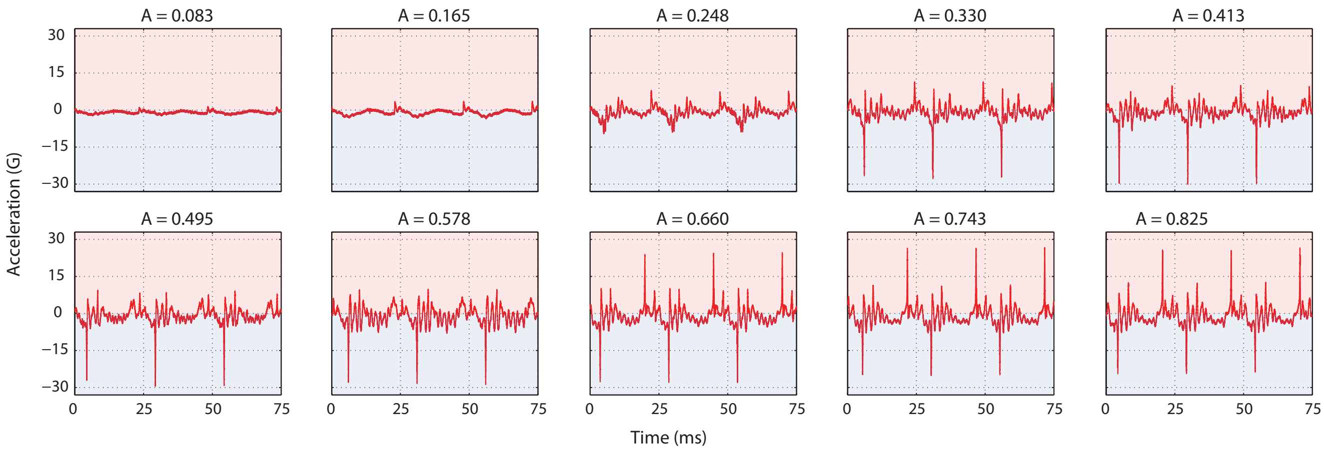

Figure 8. Acceleration change by changing the magnitude of asymmetric vibration. A is amplitude of current output.

However, with the arrangement of voice coil actuators in Grabity, the asymmetric vibration can only generate virtual forces in the direction of the axis of voice coils (1DOF).

Sensing

An OptiTrack motion tracking system is used to track the position and orientation of the thumb. A magnetic encoder is attached to the index finger sliding assembly to track it's position relative to the thumb. The encoder is friction driven and rolls on the prismatic joint (carbon fiber tube). Using the data from the motion tracking system and magnetic encoder, we can render user's thumb and index finger in VR.

The resolution of the magnetic encoder and friction drive assembly was measured to be 2 mm of linear travel. This resolution is sufficient based on just noticeable difference (JND) results of fingers to thumb distance perception [42]. Our Wolverine system [10] had a Time-of-Flight sensor to measure this distance with a resolution of 1 mm; however, it also had ± 1 mm noise with 100 Hz sampling rate. By adapting the magnetic encoder, we can achieve much lower noise and much higher sampling rate (kHz), at the cost of resolution.

Software: Virtual Reality Haptics Framework

The Grabity software framework is implemented in C++ and uses multiple software libraries. As a virtual haptic device, Grabity requires knowledge of its position as input and produces force as output. The information flow begins with position tracking of Grabity with the OptiTrack motion tracking system. The framework gets the 6DOF pose through the Motive C++ API. The grasping distance is transferred over the Teensy's serial link (2,000,000 bits per second) from the encoder in the Grabity device's slider.

In CHAI3D (version 3.2.0), Grabity is represented as a subclass of the cGenericHapticDevice that accesses both the device position and the grasping distance. CHAI3D integration for Open Dynamics Engine (ODE) renders the physical interactions. The display appears on the Oculus VR headset, and the force output given by ODE is passed along to the cGrabityDevice class. The force is further separated into its components as it is to the Teensy microcontroller.

Mass Simulation during Grasping

CHAI3D provides the output force, torque, and gripper force to the custom haptic device. Because Grabity has only two modes of actuation, these virtual values need to be converted into a voice coil signal and a command to lock the slider. The locking occurs when the gripper force (the force pushing apart the thumb and finger, i.e., from gripping a block) is greater than an empirically determined threshold of 0.7 N. This value was chosen to avoid locking when one finger strikes a block, but trigger locking quickly when a block is grasped.

Determining the voice coil signal is more complex. First, we must assume the voice coil is always pointing downward. This assumption is not always correct, as the coils swing on a limited range and only in one dimension. However, we have found that most hand orientations the subjects use are sufficiently close to this approximation. As such, we use the output force's z-component and ignore the other two.

Second, we must separately extract the downward force for each of the two fingers. This information is encoded in the torque. As previously, we approximate the voicecoil directions as downward. We thus project the finger-to-thumb vector to the ground plane, and use that vector to convert torque back to force, and add it to the z-output-force. This force value is transmitted over the serial link to the Teensy microcontroller.

In the Teensy, the force is mapped to a voice coil signal. We use the data from the first user study, below, to construct the mapping from virtual force to amplitude. The amplitude of the signal is capped so that forces larger than can be expressed by the voicecoil are expressed by the maximum force possible.

EVALUATION

We evaluate the performance of Grabity in both quantitative and qualitative ways. First, we investigate acceleration changes versus the magnitude of asymmetric signals to find the optimal range of current to generate compelling virtual forces. Second, we quantify the magnitude of virtual forces with respect to the normal direction to ground (down and up) in a user study. We also investigate if we can change the perceived magnitude of virtual forces by changing the amplitude of the asymmetric vibrations. Third, in a second user study,

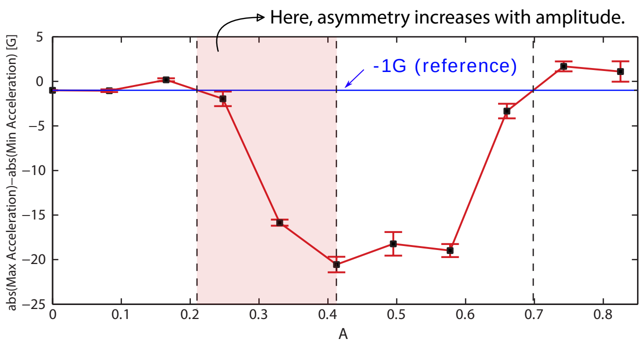

Figure 9. Acceleration asymmetry vs. Amplitude of Current.

based on the quantitative data, we give different amounts of virtual forces to users in a virtual environment and record qualitative feedback.

Acceleration Asymmetry vs. Current Magnitude

It is important that the users' finger pads receive the desired asymmetric vibration to feel the intended virtual force feedback. To evaluate the performance of the commanded asymmetric vibration, we attached an accelerometer (ADXL150) to the base part and measured the acceleration of the device while asymmetric vibrations were played. The device was fixed with clamps to the ground.

We measured acceleration with different magnitudes to determine the relationship between them. The voice coil's current amplifier operates between -0.825 A to 0.825 A (with a gain of 0.5 A/V and -1.65 V to 1.65 V signal range from Teensy). We evenly divided the amplifier's current range into 10 different magnitudes of current, and played asymmetric vibrations at different magnitudes through the voice coils. Figure 8 shows the resulting measured accelerations. Note that positive values are directed upward from ground, and negative values are directed downward towards ground.

To more clearly see the asymmetry of the accelerations, we subtracted the absolute value of the minimum acceleration from the absolute value of the maximum acceleration. The results are shown in Figure 9. When the amplitude is small ($A < 0.21$), the current is not large enough to generate asymmetry in the accelerations. For current values in the middle range ($0.21 < A < 0.42$), the asymmetry of acceleration increases proportionally to the amplitude of current. After a certain magnitude ($A > 0.42$), an increase in current resulted in a decrease in asymmetry of the acceleration signal. The direction of the asymmetric acceleration was switched when the magnitude increased even more ($A > 0.7$). This is due to a limitation of the voice coil actuator we chose. The coil and permanent magnet are connected with elastic membranes. Once the current exceeds a certain threshold ($A < 0.42$), spring forces from the membranes are so large that the magnet cannot move further, and it receives a large force pulling it backward. A voice coil actuator with a softer or no membrane would help this in the future. Based on this experiment, we choose amplitudes (A) of 0.248, 0.330 and 0.413 for the following evaluation.

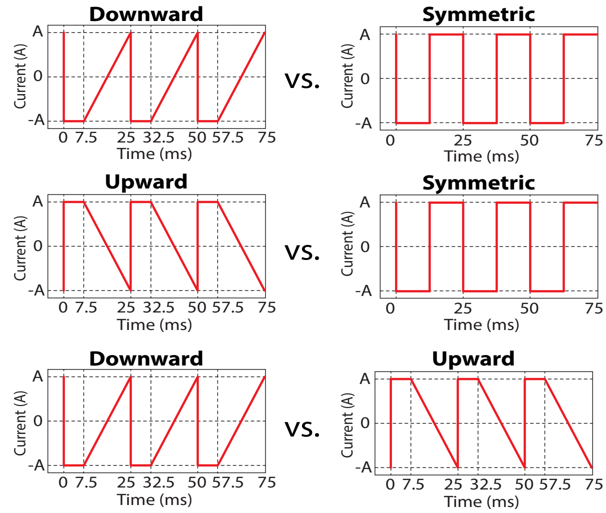

Figure 10. Virtual forces through asymmetric vibration were quantified in 3 conditions. Downward Asymmetric vs. Symmetric (Top), Upward Asymmetric vs. Symmetric (Middle), Downward Asymmetric vs. Upward Asymmetric (Bottom). 3 different current magnitudes were tested in each condition.

User Study 1: Virtual Forces Measurement

The purpose of this task is to quantify the magnitude of virtual forces. First, we evaluate the perceived magnitude of the virtual force by changing the amplitude of the asymmetric signal. Second, we aim to measure the virtual force with three different conditions to create weight sensations: downward directed force, upward directed force, and the perceived force difference between downward and upward directed forces. Figure 10 shows condition sets for virtual force quantification. To achieve the first goal, we use three different magnitudes ($A \in \{0.248, 0.330, 0.413\}$) chosen for their different acceleration profiles as shown in Figure 9. To achieve the second goal, we compare downward asymmetric vibrations with symmetric vibrations, upward asymmetric vibrations with symmetric vibrations, and downward asymmetric vibrations with upward asymmetric vibrations. The two compared vibrations always have the same current amplitude.

We have two hypotheses:

Hypothesis 1: The magnitude of perceived virtual forces can be manipulated with the amplitude of the asymmetric vibration signal, for both downward and upward directed forces (normal to ground).

Hypothesis 2: Comparing from a baseline of an upward virtual force reference, a downward virtual force will increase the perceived force difference.

Task and Procedure

During this task, participants compared two weights multiple times relying on the virtual force sensation. We used the staircase method [11] to measure the amount of virtual forces with a reference weight of 65 grams (the device weight) and a step-size of 5.4 grams, which was decided based on pilot tests. Physical weights were added to one of the comparison vibration patterns, as shown in 12 (right), according to the staircase method. Participants were wearing a blindfold, earplugs, and

Table 1. Weight Equivalence p-values, Bonferroni corrected, **p<0.005, ***p<0.0005, + means adjusted p-value is greater than 1

Signal	Low, Down	Mid, Down	High, Down	Low, Up	Mid, Up	High, Up	Low, Both	Mid, Both
Mid, Down	0.16							
High, Down	0.0014**	+						
Low, Up	0.23	<0.0001***	<0.0001***					
Mid, Up	0.0006**	<0.0001***	<0.0001***	+				
High, Up	<0.0001***	<0.0001***	<0.0001***	0.20	+			
Low, Both	+	0.033	0.0002***	0.96	0.0043**	0.0001***		
Mid, Both	0.49	+	+	<0.0001***	<0.0001***	<0.0001***	0.11	
High, Both	0.0004***	+	+	<0.0001***	<0.0001***	<0.0001***	<0.0001***	+

Figure 11. Virtual force measuring experiment setup. Right: Device with added physical weights.

noise canceling headphones playing white noises to eliminate possible effects that may arise from visual and audio cues. To avoid possible effects from different sizes, the device was always fixed to give users a 70 mm grasping distance.

First, participants were trained for 5 minutes on how to grasp the device correctly and were shown the different asymmetric vibration cues. Then, participants were guided through a staircase procedure to determine the perceived force. The experimenter handed the device to participants. Once the participants said they are ready to measure the weight, the experimenter set the baseline signal, and the participants moved their hands up and down three time to measure and remember its weight. Once they stopped the motion, the experimenter took the device, changed the vibration signal, and gave the device again to participants. Participants repeated the motion, then decided which one was heavier. The experimenter then added the step-sized physical weight to the signal that participants determined felt lighter. This procedure was repeated until the "lighter" signal reversed (from baseline signal + weight to asymmetric signal or vice versa) three times. The recorded weight is the average of the three reversal points.

Participants

12 participants (6 female, 6 male) were recruited for the experiment. All participants were right-handed and 24–29 years old. Their hand sizes (length from bottom of palm to the end of the middle finger) varied 14–21 cm. Four participants responded that they had never tried haptic devices, besides those in cellphones or commercial game controllers. The subjects received a nominal compensation ($15) for their participation.

Results

The results of this first user study are shown in Figure 12. We analyzed the results using a one-way repeated

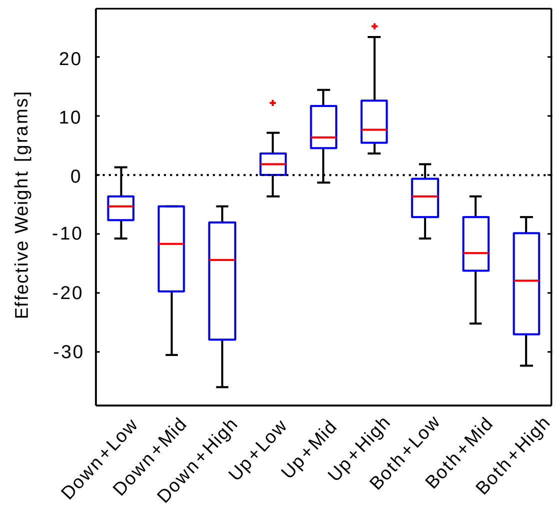

Figure 12. Result of virtual force measurement task

measures ANOVA. We found a significant effect of Signal on Weight (F(8,90)=12.1, p<0.001, η^2=0.51 with CI=[0.30, 0.57]). Bonferroni-corrected significance measures are given in Table 1.

Discussion

Our first hypothesis, that the magnitude of the virtual force can be manipulated with the amplitude of the asymmetric signal, was supported by the data. Most of the comparisons between upward and downward forces were significant. In addition, the low and the high amplitude signals in the downward force case were shown to be significantly different. However, there was not any statistical significance between the Mid Down and other Down conditions. We believe this could be due to the nonlinearity of asymmetric responses of the three current levels. As shown in Figure 9 the higher current levels, which correspond to mid Down and high Down, were closer in asymmetry. Another effect may be the time between the comparisons as well as the fact that the step-size for the reference weight was close to the just noticeable difference for weight perception. In addition, finger pad placement and grip force have a strong effect on the asymmetric skin stretch. Although we instructed the participants to have a consistent grip throughout out the experiment, given the duration of the study and the number of times the device was gripped during the study, it seems likely that this was inconsistent within and certainly between users. Finally, finger size and other anthropometric factors seem to play a role in sensitivity to asymmetric skin

Figure 13. Integration of Grabity with VR setup for tasks

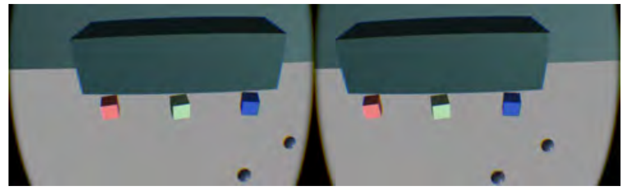

Figure 14. Weight sorting task.

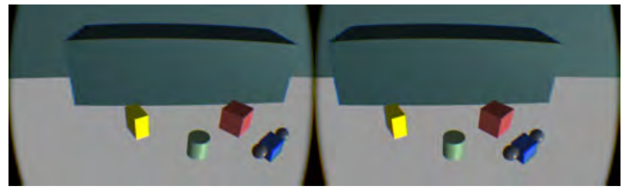

Figure 15. Free activity using Grabity in VR for qualitative feedback.

stretch. Thus, while the results are encouraging we believe further study is needed to collect more controlled data. However, these results should give a good impression of real world performance where many different users might use a generic haptic device.

However, we found no evidence to support our second hypothesis, that providing a baseline upward force to compare the downward force to would increase the perceived force difference. This result is particularly interesting, because we have modeled the effect of asymmetric skin deformation as an additive factor. This could be due to the time between which participants felt the stimuli because it took some time for the experimenter to add weight, so changes were not instantaneous. An immediate *up-then-down* signal may provide a more noticeable delta. In addition, because the physical weights were added most often to the *up* reference signal, users had conflicting weight cues. Some users reported that they perceived the physical weights as mass and the *up* signal as a pulling force, not less mass. This suggests that physical weight or mass cannot be "offset" by a virtual force.

User Study 2: Discriminating weights in a Virtual Environment

In the first user study, we investigated whether different magnitudes of asymmetric vibrations create different perceived virtual forces. In this section, we test the ability of users to discriminate between different simulated weights with a VR setup shown in Figure 13. Furthermore, we gather qualitative feedback about using Grabity for VR applications.

Task and Procedure

In a virtual reality environment, the participant manipulates three blocks with different virtual masses using Grabity, see Figure 14. The experimenter instructs the participant to sort these blocks in the manipulation space from lightest on the left to heaviest on the right. The force of weight from a block is simulated by one of three voice coil signals used during the first user study (A = 0.248, 0.330, 0.413). The participant completes 6 rounds of the sorting experiment. To avoid the color effect on the weight of objects, we randomized the colors for every round. We also informed users before starting the task that colors do not have a relationship with weights.

After the 6 rounds, the experimenter changed the virtual reality environment to contain four objects: a small box, large box, flat box, and cylinder. The participant was allowed to freely explore these objects for 3 minutes before being asked to fill out a qualitative questions.

In order for the participants to become accustomed to the skin deformation actuator and the handheld haptic device, they are shown the maximum asymmetric vibration upward and downward cues before the study began. Then, in the first virtual environment in the study, there is one virtual block, which the experimenter instructs the subject to manipulate until they are comfortable picking up and moving it. As in the first user study, the participant wore a headset, earplugs, and headphones playing white noise.

The power of the signal the participants feels does not respond to acceleration or tilting, only to whether the user is grasping a block and the mass of that block. However, during the free-play exploration mode, the actuator simulates a continuous range of forces. During this mode, natural physical effects, like forces and torques due to acceleration, are rendered by Grabity. We wished to show the widest expressiveness of our device possible when receiving qualitative feedback.

Participants

5 participants (1 female, 4 male) participated in the task. Participants in this group did not overlap with participants of the first user study. All participants were right-handed and 23-28 years old. 2 participants responded that they had never tried VR applications. Participants did not receive compensation for this short task.

Results

The confusion matrix is shown in Figure 16.

Using the Kruskal-Wallis nonparametric test, we show a significant effect of virtual weight on ordering ($\chi^2(2)$=30.95, $p < 0.001$). A post-hoc test using Mann-Whitney tests with Bonferroni correction showed significant differences among all groups. The groups Light and Heavy are different ($p < 0.001$, r=1.06), Light and Medium are different ($p < 0.001$, r=0.79), and Medium and Heavy are different ($p < 0.05$, r=0.50).

		Stimuli		
		Light (A = 0.248)	Medium (A = 0.330)	Heavy (A = 0.413)
Response	Light	21	6	3
	Medium	7	15	8
	Heavy	2	9	19

Figure 16. Confusion matrix of sorting different weights task.

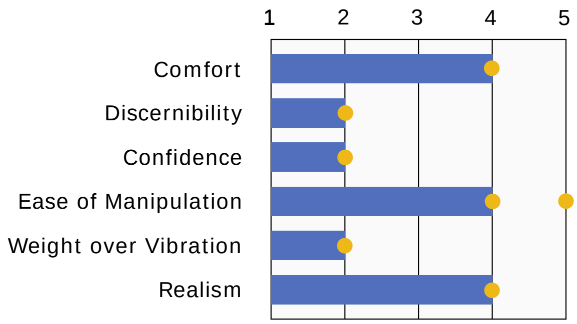

Figure 17. Medians from Likert scale survey questions in blue. Modes are marked by yellow circles.

The post-test questionnaire contains six Likert scale questions about the usability of the device, shown in Figure 17.

We collected user statements on the holistic experience of Grabity as well as on the sensation for grasping virtual objects. Every user mentioned that the weight-sorting task was difficult: "...oftentimes I could not tell the difference between the two weights," and "distinguishing between similar sized weights was quite challenging." Users appreciated the ungrounded quality of Grabity: "It is nice to be able to grab virtual objects without being tethered," and were surprised at the virtual force sensation: "In the 'heaviest' setting it really felt like my hand was being pulled down, and on the 'lightest' my hand felt like it was floating up."

Discussion

The users' rankings showed significant differences among the different virtual weights. However, as evidenced by the qualitative results, users found it difficult to tell which block weighed the most. In addition, users felt stronger vibration cues than weight cues. The amplitude of the signal, as opposed to the virtual weight, is a confounding factor.

LIMITATIONS AND FUTURE WORK

While our results indicate that asymmetric skin stretch can indeed enhance grasping interactions in VR, we also identified numerous challenges, which we hope to address in future work. We are particularly interested in quantifying the effect of vibration on force rendering realism. While we are able to mask the vibration sounds using earplugs and noise-canceling headphones, there is still a perceivable vibratory effect, and we would like to better understand its influence on the force sensation. Further, we would like to quantify how the perception of force rendering changes over time, as it is known that our mechanoreceptors are designed to gradually accommodate and cancel out vibration feedback. In addition, because Grabity uses a pair of voice coil actuators, theoretically, torques could be rendered. While we have experienced this in the lab, further study to quantify and understand this effect is necessary.

We are also interested in exploring different types of voice coil actuators or other actuation technologies that can enable stronger effects. Additionally, sensing of grip force (through pressure sensors) and finger pad placement (through capacitive sensing arrays) could help provide more robust and consistent virtual forces for different users and across different grip styles. Attaching the device to the user's fingers (important for allowing them to open the gripper) also continues to pose problems both for dampening and for transmitting vibrations to the dorsal area of the finger, which can limit the skin stretch cues. Better techniques and mechanical designs for finger pad grounding need to be explored. Beyond this, a large limitation remains that asymmetric skin stretch can only render virtual forces tangentially to the finger pad – not normal to it. One approach may be to combine skin stretch with a rotational momentum-based pseudo-force rendering technique, such as motor rotational acceleration [46], which could provide the sensation of torques in an axis that asymmetric skin stretch can not support.

Finally, we would like to formally evaluate our approach in comparison with grounded, stationary haptic devices. This would, for example, allow us to assess the impact of our limitations of only supporting lateral motions on the skin stretching surface. Through the insight gathered from additional experiments, we would hope to provide a broader set of design guidelines for mobile, ungrounded haptics.

CONCLUSIONS

In this work, we introduced *Grabity*, which focuses on enhancing the grasping sensation for virtual objects through kinesthetic feedback for *contact*, *grasping*, *gravity* and *inertia*. We contribute a novel, unified design based on the combination of vibrotactile feedback, uni-directional brakes, and asymmetric skin stretch. Our gripper-style haptic device generates opposing forces between the index finger and thumb, and uses a skin stretch mechanism, to render inertia and mass.

While portable devices exist that provide haptic feedback, these are generally limited in the type of sensation that can be generated given the difficulty to simulate weight and inertia without mechanically grounded hardware. Grabity demonstrates how such limitations can be overcome in mobile, ungrounded mechanical designs, while advancing the research into asymmetric skin stretch as a means for haptic force rendering.

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REFERENCES

1. CyberGrasp, CyberGlove Systems Inc. http://www.cyberglovesystems.com/cybergrasp/. (????). Accessed: 2017-04-03.
2. Tomohiro Amemiya and Hiroaki Gomi. 2014. Distinct pseudo-attraction force sensation by a thumb-sized vibrator that oscillates asymmetrically. In *International Conference on Human Haptic Sensing and Touch Enabled Computer Applications*. Springer, 88–95.
3. Tomohiro Amemiya and Taro Maeda. 2008. Asymmetric oscillation distorts the perceived heaviness of handheld objects. *IEEE Transactions on Haptics* 1, 1 (2008), 9–18.
4. AA Amis. 1987. Variation of finger forces in maximal isometric grasp tests on a range of cylinder diameters. *Journal of biomedical engineering* 9, 4 (1987), 313–320.
5. Federico Barbagli, Kenneth Salisbury, and Roman Devengenzo. 2004. Toward virtual manipulation: from one point of contact to four. *Sensor Review* 24, 1 (2004), 51–59.
6. Karlin Bark, Jason Wheeler, Gayle Lee, Joan Savall, and Mark Cutkosky. 2009. A wearable skin stretch device for haptic feedback. In *EuroHaptics conference, 2009 and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. World Haptics 2009. Third Joint*. IEEE, 464–469.
7. 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, 717–728.
8. Mourad Bouzit, Grigore Burdea, George Popescu, and Rares Boian. 2002. The Rutgers Master II-new design force-feedback glove. *IEEE/ASME Transactions on mechatronics* 7, 2 (2002), 256–263.
9. Francesco Chinello, Monica Malvezzi, Claudio Pacchierotti, and Domenico Prattichizzo. 2015. Design and development of a 3RRS wearable fingertip cutaneous device. In *Advanced Intelligent Mechatronics (AIM), 2015 IEEE International Conference on*. IEEE, 293–298.
10. 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 *Intelligent Robots and Systems (IROS), 2016 IEEE/RSJ International Conference on*. IEEE, 986–993.
11. Tom N Cornsweet. 1962. The staircase-method in psychophysics. *The American journal of psychology* 75, 3 (1962), 485–491.
12. Heather Culbertson, Julie M Walker, and Allison M Okamura. 2016. Modeling and design of asymmetric vibrations to induce ungrounded pulling sensation through asymmetric skin displacement. In *Haptics Symposium (HAPTICS), 2016 IEEE*. IEEE, 27–33.
13. Heather Culbertson, Julie M Walker, Michael Raitor, and Allison M Okamura. 2017. WAVES: A Wearable Asymmetric Vibration Excitation System for Presenting Three-Dimensional Translation and Rotation Cues. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. ACM, 4972–4982.
14. Takahiro Endo, Haruhisa Kawasaki, Tetsuya Mouri, Yasuhiko Ishigure, Hisayuki Shimomura, Masato Matsumura, and Kazumi Koketsu. 2011. Five-fingered haptic interface robot: HIRO III. *IEEE Transactions on Haptics* 4, 1 (2011), 14–27.
15. 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*. ACM, 1991–1995.
16. Sidhant Gupta, Tim Campbell, Jeffrey R Hightower, and Shwetak N Patel. 2010. SqueezeBlock: using virtual springs in mobile devices for eyes-free interaction. In *Proceedings of the 23nd annual ACM symposium on User interface software and technology*. ACM, 101–104.
17. Vincent Hayward and M Cruz-Hernandez. 2000. Tactile display device using distributed lateral skin stretch. In *Proceedings of the haptic interfaces for virtual environment and teleoperator systems symposium*, Vol. 69. ASME, 1309–1314.
18. James Houk and William Simon. 1967. Responses of Golgi tendon organs to forces applied to muscle tendon. *Journal of neurophysiology* 30, 6 (1967), 1466–1481.
19. Alexandra Ion, Edward Jay Wang, and Patrick Baudisch. 2015. Skin drag displays: Dragging a physical tactor across the user's skin produces a stronger tactile stimulus than vibrotactile. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. ACM, 2501–2504.
20. RS Johansson and G Westling. 1984. Roles of glabrous skin receptors and sensorimotor memory in automatic control of precision grip when lifting rougher or more slippery objects. *Experimental brain research* 56, 3 (1984), 550–564.
21. Kenneth O Johnson. 2001. The roles and functions of cutaneous mechanoreceptors. *Current opinion in neurobiology* 11, 4 (2001), 455–461.
22. Lynette A Jones. 1986. Perception of force and weight: Theory and research. *Psychological bulletin* 100, 1 (1986), 29.
23. Rebecca Khurshid, Naomi Fitter, Elizabeth Fedalei, and Katherine Kuchenbecker. 2016. Effects of Grip-Force, Contact, and Acceleration Feedback on a Teleoperated Pick-and-Place Task. *IEEE transactions on haptics* (2016).

24. Katherine J Kuchenbecker, Jamie Gewirtz, William McMahan, Dorsey Standish, Paul Martin, Jonathan Bohren, Pierre J Mendoza, and David I Lee. 2010. VerroTouch: High-frequency acceleration feedback for telerobotic surgery. In *International Conference on Human Haptic Sensing and Touch Enabled Computer Applications*. Springer, 189–196.

25. Susan J Lederman and Roberta L Klatzky. 1987. Hand movements: A window into haptic object recognition. *Cognitive psychology* 19, 3 (1987), 342–368.

26. Christine L MacKenzie and Thea Iberall. 1994. *The grasping hand*. Vol. 104. Elsevier.

27. Thomas H Massie, J Kenneth Salisbury, and others. 1994. The phantom haptic interface: A device for probing virtual objects. In *Proceedings of the ASME winter annual meeting, symposium on haptic interfaces for virtual environment and teleoperator systems*, Vol. 55. Citeseer, 295–300.

28. William McMahan and Katherine J Kuchenbecker. 2014. Dynamic modeling and control of voice-coil actuators for high-fidelity display of haptic vibrations. In *Haptics Symposium (HAPTICS), 2014 IEEE*. IEEE, 115–122.

29. Kouta Minamizawa, Souichiro Fukamachi, Hiroyuki Kajimoto, Naoki Kawakami, and Susumu Tachi. 2007a. Gravity grabber: wearable haptic display to present virtual mass sensation. In *ACM SIGGRAPH 2007 emerging technologies*. ACM, 8.

30. Kouta Minamizawa, Hiroyuki Kajimoto, Naoki Kawakami, and Susumu Tachi. 2007b. A wearable haptic display to present the gravity sensation-preliminary observations and device design. In *EuroHaptics Conference, 2007 and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. World Haptics 2007. Second Joint*. IEEE, 133–138.

31. Jun Murayama, Laroussi Bougrila, YanLin Luo, Katsuhito Akahane, Shoichi Hasegawa, Béat Hirsbrunner, and Makoto Sato. 2004. SPIDAR G&G: a two-handed haptic interface for bimanual VR interaction. In *Proceedings of EuroHaptics*, Vol. 2004. 138–146.

32. Zoran Najdovski and Saeid Nahavandi. 2008. Extending haptic device capability for 3D virtual grasping. *Haptics: perception, devices and scenarios* (2008), 494–503.

33. Ryuma Niiyama, Lining Yao, and Hiroshi Ishii. 2014. Weight and volume changing device with liquid metal transfer. In *Proceedings of the 8th International Conference on Tangible, Embedded and Embodied Interaction*. ACM, 49–52.

34. Claudio Pacchierotti, Gionata Salvietti, Irfan Hussain, Leonardo Meli, and Domenico Prattichizzo. 2016. The hRing: A wearable haptic device to avoid occlusions in hand tracking. In *Haptics Symposium (HAPTICS), 2016 IEEE*. IEEE, 134–139.

35. Jérôme Pasquero and Vincent Hayward. 2003. STReSS: A practical tactile display system with one millimeter spatial resolution and 700 Hz refresh rate. In *Proc. Eurohaptics*, Vol. 2003. 94–110.

36. Christopher J Ploch, Jung Hwa Bae, Wendy Ju, and Mark Cutkosky. 2016. Haptic skin stretch on a steering wheel for displaying preview information in autonomous cars. In *Intelligent Robots and Systems (IROS), 2016 IEEE/RSJ International Conference on*. IEEE, 60–65.

37. William Provancher. 2014. Creating greater VR immersion by emulating force feedback with ungrounded tactile feedback. *IQT Q* 6, 2 (2014), 18–21.

38. William R Provancher and Nicholas D Sylvester. 2009. Fingerpad skin stretch increases the perception of virtual friction. *IEEE Transactions on Haptics* 2, 4 (2009), 212–223.

39. Zhan Fan Quek, Samuel B Schorr, Ilana Nisky, William R Provancher, and Allison M Okamura. 2015. Sensory substitution and augmentation using 3-degree-of-freedom skin deformation feedback. *IEEE transactions on haptics* 8, 2 (2015), 209–221.

40. Jun Rekimoto. 2014. Traxion: a tactile interaction device with virtual force sensation. In *ACM SIGGRAPH 2014 Emerging Technologies*. ACM, 25.

41. Samuel B Schorr and Allison M Okamura. 2017. Fingertip Tactile Devices for Virtual Object Manipulation and Exploration. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. ACM, 3115–3119.

42. Hong Z Tan, Xiao Dong Pang, Nathaniel I Durlach, and others. 1992. Manual resolution of length, force, and compliance. *Advances in Robotics* 42 (1992), 13–18.

43. Nikolaos G Tsagarakis, T Horne, and Darwin G Caldwell. 2005. Slip aestheasis: A portable 2d slip/skin stretch display for the fingertip. In *Eurohaptics Conference, 2005 and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2005. World Haptics 2005. First Joint*. IEEE, 214–219.

44. Ernst Heinrich Weber, Helen Elizabeth Ross, and David J Murray. 1996. *EH Weber on the tactile senses*. Psychology Press.

45. Vibol Yem, Ryuta Okazaki, and Hiroyuki Kajimoto. 2016a. FinGAR: combination of electrical and mechanical stimulation for high-fidelity tactile presentation. In *ACM SIGGRAPH 2016 Emerging Technologies*. ACM, 7.

46. Vibol Yem, Ryuta Okazaki, and Hiroyuki Kajimoto. 2016b. Vibrotactile and pseudo force presentation using motor rotational acceleration. In *Haptics Symposium (HAPTICS), 2016 IEEE*. IEEE, 47–51.

47. André Zenner and Antonio Krüger. 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 (2017), 1285–1294.