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Mass Simulation in VR using Vibrotactile Feedback and a Co-located Physically-Based Virtual Hand

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ABSTRACT

Virtual reality allows for highly immersive simulated experiences and interaction with virtual objects. However, virtual objects do not have real masses. Providing the sense of mass for virtual objects using un-grounded haptic interfaces has proven to be a complicated task in virtual reality. This paper proposes using a physically-based virtual hand with improved co-location and a complementary vibrotactile effect on the index fingertip to give the sensation of mass to objects in virtual reality. The vibrotactile feedback is proportional to the balanced forces acting on the virtual object and is modulated based on the object's velocity. For evaluating this method, we set an experiment in a virtual environment where participants wear a VR headset and attempt to pick up and move different virtual objects using a virtual physically-based hand while a voice-coil actuator attached to their index fingertip provides the vibrotactile feedback. Our experiments indicate that the virtual hand and our vibration effect give the ability to discriminate and perceive the mass of virtual objects.

1. Introduction

Virtual Reality (VR) has significantly revolutionized simulated human experiences. VR enables an immersive virtual experience by simulating and triggering most of our senses as if we are present in another environment. Notably, in VR it is possible to see one's own co-located virtual hands, perceive them as their own real hands and interact with virtual objects [1]. However, virtual objects have no real mass, and the problem is including touch and visual cues that we rely on for mass perception. The physical cues include skin stretch and contact pressure at the fingertips (cutaneous feedback) and proprioceptive feedback from multiple muscles and joints (kinesthetic feedback).

Grounded haptic devices can render the necessary forces for kinesthetic and cutaneous haptic feedback. However, their size, weight, and limited workspace restrict free-hand movements, making them less desirable in various VR applications.

Alternatively, ungrounded haptic devices (such as finger-mounted or hand-held devices) can be built more compactly and lighter, making them more convenient to use in a larger workspace. Sensing the mass of a virtual object in every direction needs more complex ungrounded hardware with higher degrees of freedom. However, such devices require multiple actuators and can limit hand and finger movements.

Another approach to overcome the hardware limitations is to use visio-haptic illusions. These methods aim to trick the brain into perceiving the mass by manipulating the objects' visual cues. For example, limiting the virtual object's velocity [2], or scaling its displacement compared to the user's hand [3] are shown to give a sense of mass to the objects. However, these methods are not physically realistic or decrease the co-location between the actual and virtual hands.

In this paper, we extend and improve our novel mass rendering method [4] that combines a visio-haptic technique with a simple finger-mounted vibration actuator. For the visio-haptic

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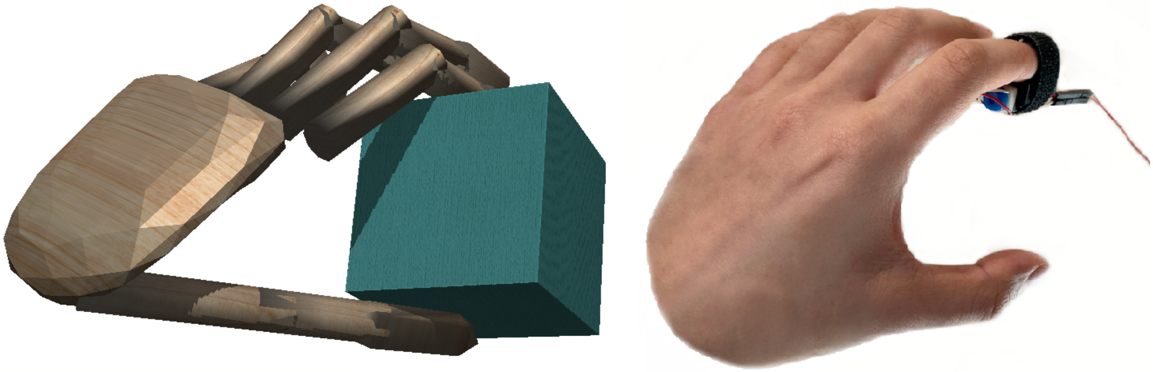


Fig. 1: Physics-based interactions with virtual objects using a co-located virtual hand (the left figure) are augmented using vibrational feedback proportional to objects' mass and acceleration (the right figure).

part, we replicate the visual cues that humans perceive during a real-world hand interaction with physical objects. We use a physically-based virtual hand in VR to interact with virtual objects, which results in a limit on the heaviness of the objects that the user can pick up and how fast they can accelerate them based on their mass. Moreover, we improve the co-location between the physically-based virtual hand and the user's actual hand compared to traditional methods. However, it is difficult to distinguish between light objects using this technique. We complement our visio-haptic method with haptic feedback. The haptic actuator that renders the feedback should be small and compact enough to allow individual fingers to move independently and perform dexterous interactions. Also, we prefer an ungrounded device since it allows a larger workspace. One method to reduce the device's size is to use haptic feedback that is directionally invariant to our sense of touch. If the haptic stimulus's direction is detectable by the sense of touch, we need multiple actuators to render the haptic effect in different directions during a virtual interaction. Therefore we employ an ungrounded, direction invariant haptic effect to complement our physically-based virtual hand. We explore using a mechanical vibration feedback effect to achieve ungrounded mass rendering for virtual objects. In our work, while the virtual object is in the user's grasp, a sinusoid vibration proportional to the object's mass and acceleration is played through an ungrounded voice-coiled actuator at the tip of the user's index finger. An overview of the proposed method is shown in Fig. 1.

When moving two objects with different mass, in addition to the physically-based visio-haptic feedback, users feel proportionally stronger vibration while grasping the heavier object. This vibrotactile feedback gives the user a clue to the net force acting on the virtual object. To make this a direction-invariant haptic feedback, we use frequencies above 100Hz. These frequencies are sensed by Pacini mechanoreceptors, which are not sensitive to the stimuli's directions.

To evaluate the proposed physically-based virtual hand and the vibration feedback, we conducted a user study where participants interact with virtual objects with different masses and perform virtual tasks. Using qualitative and quantitative methods, we show that the physically-based hand gives a sense of mass to virtual objects, and adding the vibration feedback does improve mass perception and discrimination.

The main contribution of this work is the design, development, and evaluation of a novel mass rendering method for virtual objects using physically-based hand-object interactions and vibration feedback. An abridged version of this work is published at the Graphics Interface 2021 conference [4]. This extended version includes an expanded discussion of related work on mass rendering and hand tracking, additional illustrations for our user study, and an extended discussion on future research directions. Also, we have a new section for analyzing the co-location of our modified physically-based section (see section 3.2).

2. Related Work

In this section, we review research focused on interaction with virtual objects in a VR environment, including studies on the sense of presence, immersion, realism, and performance. Then, we look at different modes of interaction in VR, especially grasping and interacting using the user's own co-located virtual hands and different techniques and hardware used for hand-tracking. We also discuss techniques and devices that enable users to perceive the mass of an object in a virtual environment. These include the use of grounded and ungrounded haptic devices, which further divide into wearable and hand-held devices, and the use of visual and haptic illusions.

2.1. *Interaction in VR*

Interaction is an important part of an immersive virtual experience and increases the user's sense of presence [5, 6]. Enabling VR users to grasp a virtual object using their own co-located virtual hands requires a VR system to track the users' actual hands and provide visual or haptic feedback for grasping.

2.1.1. *Hand Tracking*

During a virtual experience, we track the user's hands to enable interaction between the co-located virtual hand and virtual objects within the scene. Hand tracking can be achieved either using a tracked VR hand-held controller or using vision-based hand tracking hardware. On the one hand, using a VR hand controller allows for a clear interpretation of users' decisions since they can use buttons on the controller to perform manual operations such as grasping. However, In VR, they will see a rendering of their virtual hand grasping an object, which contradicts the proprioceptive sense of their hand pose since it has not changed in the real world. Although, It is possible to design hand controllers to mimic the natural movement of grasping to a degree [7]; however, holding a hand controller can limit the movement of hands and fingers in general nonetheless. On the other hand, using visual hand-tracking techniques, we can track the hand's palm and individual phalanges and allow the user to move their fingers and palm at the same time freely without constraints. Therefore, creating a more realistic experience regarding how the user virtual hand responds to changes in their actual one. Lin [1] compares using VR hand controllers versus visual hand tracking (in their case, tracking a glove with markers on the hand and joints) in simple object manipulation tasks such as assembling puzzles and stacking objects. They conclude that using tracked gloves versus the VR controllers increased the hand's sense of ownership and realism. Furthermore, they show that users generally prefer hand tracking techniques even though they have better performance in object manipulation tasks using a VR hand controller.

Visual hand tracking is usually achieved using sophisticated motion capture systems such as Optitrack, which use tracking gloves with markers on them, but their complexity and price can narrow their use cases. However, nowadays, third-party add-on visual hand-tracking hardware, such as LeapMotion tracker, can be added to commercial VR headsets for a fraction of their price. The LeapMotion controller can track dynamic objects with an average error of 1.2 millimeters [8]. Moreover, Mizera et al. [9] show that the LeapMotion controller is accurate for measuring the positions of fingertips since it tracks the phalanges as oppose to joints and compared to two glove-based hand tracking systems, it was the only system that provided reliable tracking of the thumb across the workspace, even though it was not as accurate in measuring flexion and extension. Moreover, they conclude that these features make the Leapmotion tracker suitable for virtual tasks that require controlling objects between the thumb and opposing fingers distal phalanges (fingertips) such as pinch grasping.

2.1.2. *Visual Hand-Object Interaction in VR*

In VR, given the location of the actual hand, we should render a virtual hand as close as possible to the actual hand while interacting with the virtual elements in the scene in a realistic manner. There are various ways to enable visual interactions between a virtual hand and virtual objects. In gesture and metaphor-based approaches, the interaction is based on specified hand commands. If the virtual hand is in a grasping pose and near a virtual object, that object's orientation follows the virtual hand as if it has been grasped by that hand. Song et al. [10] enables nine degrees-of-freedom control of a virtual tool using bi-manual gestures. Gesture-based approaches have proven to be robust and effective. However, they are not natural as they do not follow how we use our hands in the physical world and reality; therefore, they are not suitable for a physically realistic interaction.

Another approach is to use physically-based manipulation techniques. For example, Borst and Indugula in [11] propose virtual coupling of the tracked hand to a rigid kinematic hand that enables whole hand grasping. In this method, the palm and finger joints of the tracked hand and the kinematic hand are connected to the corresponding parts using linear and torsional virtual spring-dampers. When a user attempts to pick up a virtual object using the virtual coupling technique, their actual hand penetrates the object. However, the virtual hand grasps around the object, enabling the user to interact and move the object. Moreover, since the spring damper links work based on applying a limited and proportional amount of force, this method shares the same physical limitations that a realistic interaction has. We modify this method to preserve the steady-state colocation between the virtual and actual palms and evaluate it for mass rendering in VR. The interactions of the virtual hand are more visually realistic since it does not penetrate the object. However, while grasping, the virtual hand and the actual hand's displacement might cause discrepancies between the user's visual and proprioceptive senses. Canales et al. [12] show that users prefer to see the non-penetrating virtual hand during object manipulation tasks and have higher hand ownership levels, even though they have better performance in virtual tasks when only their actual hand is visible in the scene.

2.2. *Mass Rendering Techniques*

In this subsection, we review relevant literature on simulating the mass of virtual objects during a VR experience. Humans can sense the mass of an object through their sense of touch and vision. When we pick up and interact with an object, its forces of inertia and weight are counteracted by our body, which puts pressure on our joints, tendons, and muscles and causes skin-stretch at the point of grip. Four different kinds of mechanoreceptors measure these kinesthetic and cutaneous forces and give us a sense of how much mass the object has.

2.2.1. *Grounded Haptic Devices*

Grounded haptic devices are highly sought-after in tool-mediated applications where precision and fidelity are essential such as surgical training [13, 14]. Hand wearable grounded devices have also been developed. HIRO III [15] is an example of a five-fingered grounded haptic interface, with three DoF for each of its haptic fingers and a 6 DoF base capable of providing high precision force feedback to a hand while it is attached to each of the fingertips. The main challenge with grounded devices is the limited workspace size which narrows their application domain.

2.2.2. *Ungrounded Haptic Devices*

Ungrounded haptic devices are attached to the user's body instead of a fixed point in the room and can be built more compactly and lighter, making them more convenient to use in a larger workspace. These devices are either hand-held or attached to the user's fingers, hands, or body.

Since ungrounded haptic devices are attached to the user's body, users perceive not only the feedback force but also the reaction of any actuation on their bodies. One approach to reducing this effect is ignoring proprioceptive feedback and only rendering Cuteneous feedback since studies have shown that the human brain can still perceive an object's weight using a limited set of related haptic cues [16]. Minamizawa et al. [17] introduce a fingertip mounted ungrounded haptic device called the Gravity Grabber that can create a sense of weight when grabbing virtual objects in specific orientations. Gravity Grabber achieves this using one degree of freedom for shear force feedback and another degree of freedom in the normal direction of the fingertip skin. However, since our skin can detect the direction of skin stretch, this method cannot give a sense of weight in all orientations to a virtual object. The mechanoreceptors in our skin can perceive static shear force and its direction [18] [19], and it has been shown that humans can detect the direction of tangential skin displacement at their fingertips with 95% accuracy [20]. Therefore, sensing the weight and inertia of a virtual object in all directions using static force requires a device with more complex hardware and at least three degrees of freedom, such as the works of Chinello et al. [21], and Prattichizzo et al. [22]. Such devices are mechanically complicated since they require multiple actuators and limit hand and finger movements. In our method, we use one haptic actuator to render the mass of objects in all directions since we use sinusoidal vibration feedback.

Hand-held ungrounded devices are desirable for simulating interactions with hand-held tools such as a hammer or a baseball bat. However, they limit the movement of fingers and the hand. Zenner in [23] introduced Drag:on a custom VR hand controller with two actuated fans, which can dynamically adjust the controller's aerodynamic properties, therefore changing the sensed inertia of a virtual object. Also, it can create a rotational torque if the fans open asymmetrically. Zenner et al. [24] introduce Shifty, a hand-held VR controller with an internal prismatic joint connected to a weight that shifts the center of mass of the device, resulting in different rotational inertia and resistance as the user interacts with various virtual tools. In the work of Lykke et al. [25], users have two hand controllers to pick up round virtual objects (scooping), and they should keep their hands closer together when the objects are heavier. DualVib [26] is a hand-held device that simulated the dynamic mass and feel of a grasped container with fluids or particle-like objects inside it. It uses asymmetric vibration in one direction to give kinesthetic force feedback and pre-recorded vibration feedback from actual fluids and materials to synthesize their texture during motion. Furthermore, it uses the NVIDIA FleX fluid simulator to calculate the simulated particles' mean acceleration and inertial forces in real-time.

Our work uses a single compact finger-mounted haptic actuator, which does not limit the movement of user's hand and fingers.

2.2.3. *Visio-Haptic Illusions*

In VR, simulating visual cues such as kinematic properties and size can affect the perceived weight of a virtual object.

Heineken and Schulte [27] demonstrate that size-weight illusion happens in VR as well, and the perceived weight of a hand-held object can change based on its size in VR. In other words, given the same haptic cues, a larger object in VR feels lighter.

Backstrom [2] gives the sensation of mass to virtual objects in VR by limiting the velocity of a virtual object based on how heavy it is. Such constraints on the object's movements are not physically realistic. Dominjon et al. [28] show that manipulating the control-display ratios of virtual objects can change the perceived mass in virtual environments. In other words, if a virtual object's displacement is proportionally increased compared to the user's actual hand, its mass is perceived as lighter than it is. Samad et al. [3] utilize the same technique in VR to change the perceived weight of wooden cubes. However, one downside of changing the control-display ratios is that the offset between the actual and the virtual representation of the object increases as the hand gets further away from the initial contact point. Therefore, bi-manual coordination and interaction could become difficult since the virtual hand's relative position is different from the actual hands, even if it is not moving. Another general disadvantage of Visio-haptic illusions is that they rely on the user to visually observe the virtual hand's interactions. This limits the effectiveness of these methods since users might not always look at their hands in a VR experience.

Hummel et al. [29] model a hand using a similar technique to Borst and Indugula in [11] and experiment on feeling weight based on realistic interactions. Their hand model involves using a spring-damper coupling, which reduces co-location. Also, their experiments use a 3D screen, and participants can see both their actual hand and their virtual hand; hence, participants may get additional visual feedback for mass perception, such as the distance between the virtual and actual hands. Also, they do not control for possible additional visual cues for mass in a physics simulation environment, such as the speed at which objects fall in the presence of air resistance or the way they bounce on the floor after contact. Moreover, in one of their experiments, they add a passive haptic feedback for grasping force; however, no statistically significant difference in mass discrimination is observed.

Our approach aims to give a sense of mass to objects by enabling realistic interactions with virtual objects using a head-mounted VR display and physically-based virtual hand. We also preserve the co-location between the virtual and actual palm when the hand is in a steady-state (constant acceleration of the actual palm). Moreover, in our experiments, users cannot see their actual hands, and we control for additional visual cues for mass perception. Finally, we complement our virtual hand with active vibration feedback, which significantly improves mass perception and discrimination.

2.2.4. *Vibration Feedback*

As one of the modalities of haptic feedback, mechanical vibrations can be used to simulate touch stimuli. In addition to our work, asymmetrical vibration has been used by Choi et al. [30] to simulate weight in VR. Asymmetrical vibrations are more intense in one direction than the other. These vibrations cause skin-stretch, and the user can detect their direction. Therefore, multiple actuators are required for simulating weight and inertia in all directions. Moreover, the intensity of these asymmetrical vibrations is much stronger (up to 20 g ($9.8\,\mathrm{m\,s^{-2}}$)) compare to our sinusoidal vibration feedback (less than 1 g).

In the rest of this subsection, we review relevant literature on using vibration feedback to simulate virtual force. Kildal [31] uses grain mechanical vibrations to create the illusion of compliance for a rigid box. A force sensor measures the amount of force that the user is applying to the box, then the system creates short bursts of decaying sinusoid vibration in the box, which causes the user to feel a friction force as if the rigid box was compliant. The same vibrotactile feedback has been used to simulate a button press on a rigid box [32], a virtual button in VR [33], change the perceived stiffness of a rigid VR hand controller [34], creating a sense of compliance for tangential touch [35] and the illusion of walking on a softer surface [36].

Vibration feedback has also been used to create motion effects. Seo et al. [37] simulate a moving cart's motion effects by adding vibration feedback to an fixed chair and changing the amplitude and frequency of the vibration feedback proportional to the simulated cart's angular velocity.

2.3. Summary

Hand-object interactions are an important part of an immersive VR experience. Physics-based modeling of the virtual hand can offer a realistic experience and enable physically realistic interactions with VR objects. Moreover, using accessible and efficient visual hand-tracking hardware allows VR users to have their own co-located virtual hands. Mass rendering and grasp simulation methods in VR limit the hand and finger movements or engage users in unrealistic interactions. Our physically-based interaction is realistic and preserves the co-location between the actual and virtual palms in the steady-state, and our vibration feedback works with a single actuator on the fingertip without limiting the hand and finger movements.

3. Physically-Based Virtual Hand

One of the goals of this paper is to explore the effect of a physically-based interaction on mass perception and discrimination. There is a weight limit on objects in the real world that we can pick up using our hands. Our grip strength and the force that we can apply to a grasped object are bounded. Therefore, there is a limit to how fast we can accelerate an object based on its mass. In VR, we hypothesize that physically-based interaction between the user's virtual hand and object creates a sense of mass for that object. For this purpose, we track the user's hand, couple it with a 3D model of a hand, and use a physically-based simulation for hand-object interactions.

3.1. Method

We use a vision-based hand tracking system (Leap Motion hand tracker) to allow the user's hand and fingers to move freely, providing a virtual experience analogous to real-world interaction.

For modeling the hand, we consider one rigid palm and five fingers, each of which has three rigid phalanges. Interaction between VR objects and the physically-based virtual hand is more realistic than interactions between the tracked hand and VR objects. For example, when grasping an object, the tracked hand can go inside the object, but the virtual hand grasps around the object. Therefore, we only display the physically-based virtual hand (VR hand). To make the interactions more realistic, the VR hand must be co-located and coupled with the tracked hand. To achieve this, rather than a purely geometric approach, we modify the physically-based method described by Borst and Indugula in [11]. The physically-based coupling helps us to efficiently prevent unrealistic collisions and interactions between the VR hand and objects. In the physically-based coupling method, we associate one spring-damper to each rigid component of fingers. The spring-dampers apply force to the VR hand's components to match their positions and orientations to the tracked hand's corresponding components. To achieve consistent behavior from the physical simulation, we use a fixed size VR hand. Having a fixed size for the VR hand does not directly influence efficiency in virtual object manipulation tasks, sense of hand ownership, realism, or immersion in VR [1].

The spring-damper coupling applies both force and torque to the virtual part. The force at time t, $\vec{F}(t)$, is proportional to $\Delta_{Position}(t)$, the distance between the center of the mass of the two corresponding parts and the torque at time t, $\vec{\tau}(t)$, is proportional to $\Delta_{Rotation}(t)$, the difference in their rotation. To prevent the virtual part from overshooting its target position and orientation, the spring-damper applies another force to the virtual object proportional to $\vec{V}(t)$, its linear velocity and torque proportional to $\vec{\omega}(t)$, its angular velocity. That gives:

$$\vec{F}(t) = k'_p \vec{\Delta}_{Position}(t) - k'_d \vec{V}(t), \tag{1}$$

$$\vec{\tau}(t) = k''_p \vec{\Delta}_{Rotation}(t) - k''_d \vec{\omega}(t) \tag{2}$$

where k'_p, k''_p, k'_d and k''_d are the spring-damper coefficients. These parameters, are set during the preliminary experiments to ensure that the VR hand is responsive and closely and smoothly follows the actual hand and can pick up virtual mass up to 4kg.

If we use a similar spring-damper to couple the palms, when the user holds an object using the VR hand, the distance between the VR hand and the actual hand increases until the spring-dampers' forces equal the weight of the VR hand and the object that it is holding. This causes a discrepancy between the visual and the proprioceptive sense. To solve this problem, we introduce an additional term in the spring-damper for the palms:

$$F_{\vec{Palm}}(t) = k'_p \vec{\Delta}_{Position}(t) - k'_d \vec{V}(t) + k'_i \sum_{j=0}^{t} \vec{\Delta}_{Position}(j), \tag{3}$$

$$\tau_{\vec{Palm}}(t) = k''_p \vec{\Delta}_{Rotation}(t) - k''_d \vec{\omega}(t) + k''_i \sum_{j=0}^{t} \vec{\Delta}_{Rotation}(j) \tag{4}$$

where k'_i and k''_i are spring-damper coefficients. The added summation term applies force and torque proportional to the accumulation of $\vec{\Delta}_{Position}(t)$ and $\vec{\Delta}_{Rotation}(t)$ over time. Therefore, when the user holds an object, $F_{\vec{Palm}}(t)$ and $\tau_{\vec{Palm}}(t)$ increase until the virtual palm's orientation and position match

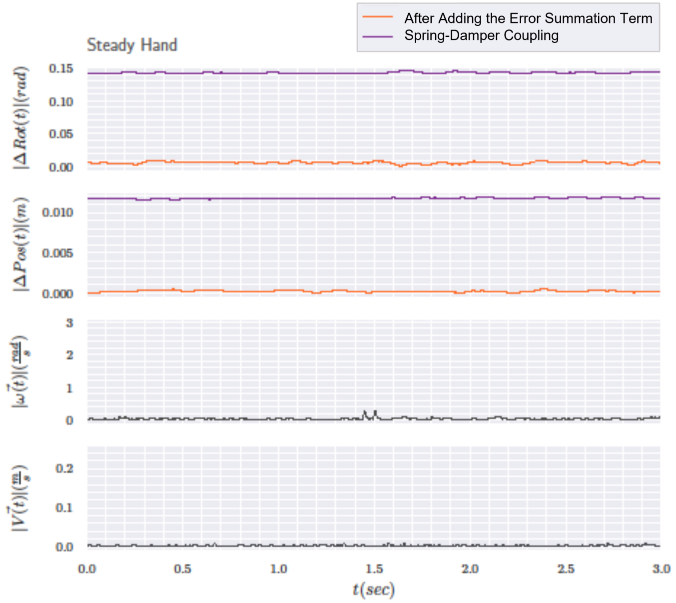


Fig. 2: Demonstrating the effect of adding the error summation term to the virtual coupling between the palms while keeping the hand steady. The orange lines show the angular difference, $|\Delta Rot(t)|$, and position difference, $|\Delta Pos(t)|$, between the actual and the virtual palm using the additional summation term. The purple line shows the likewise data for the standard spring-damper coupling. For reference, we also plot the simultaneous linear, $|\vec{V}(t)|$, and angular, $|\vec{\omega}(t)|$, speed of the actual hand.

the tracked hand palm in the steady-state. k_i' and k_i'' are set during the preliminary experiments so that position and orientation of the coupled palms quickly match when the hand is not accelerating. Also, k_p', k_p'', k_d' and k_d'' are set independently for the palm compared to the phalanges since it has different physical properties.

3.2. Analyzing Co-location

To demonstrate the effect of the error summation term, we ran an experiment and recorded the position and rotation differences of the actual and virtual palms during three different hand movements and interactions performed by a user. We use the euclidean distance between the center of the palms to measure the position error and the angle in the axis-angle representation of the rotation between the corresponding palms as the rotation error. To keep the comparison as fair as possible, we first record the hand tracker data for each of these movements. Afterward, we reset the simulation scene and use the recorded data instead of reading from the hand tracker and log the position and rotation error once with the error summation term and once without it.

For the first movement, the user tries to hold their hand in front of themselves as steady as possible while not holding or touching any objects (Fig 2). Without the summation term, the virtual hand drops around 1.15cm below the actual hand. Also, it tilts forward around 8 degrees due to the weight of the fingers in front of the palm. However, with the summation term, the position and rotation errors are much smaller. The second movement involves the user continuously moving their hand to

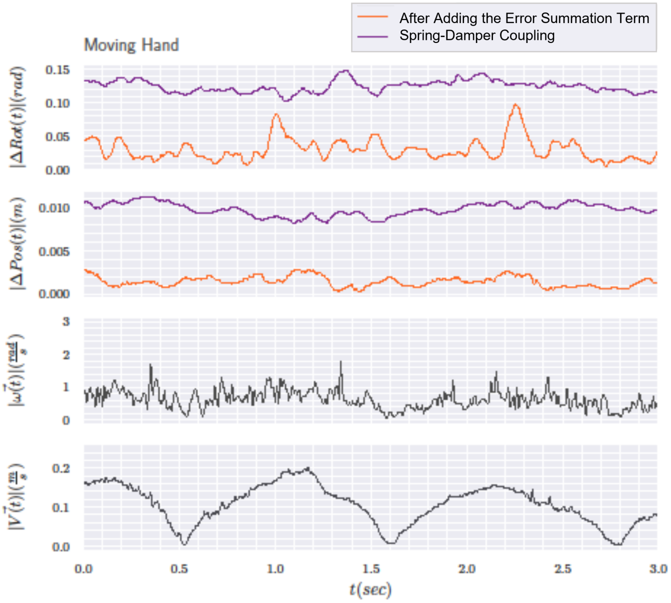


Fig. 3: Demonstrating the effect of adding the error summation term to the virtual coupling between the palms while moving the hand to left and right. The orange lines show the angular difference, $|\Delta Rot(t)|$, and position difference, $|\Delta Pos(t)|$, between the actual and the virtual palm using the additional summation term. The purple line shows the likewise data for the standard spring-damper coupling. For reference, we also plot the simultaneous linear, $|\vec{V}(t)|$, and angular, $|\vec{\omega}(t)|$, speed of the actual hand.

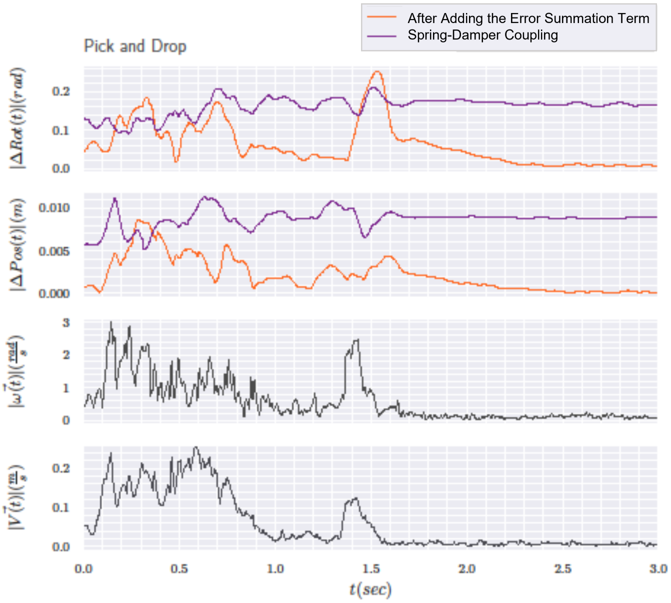
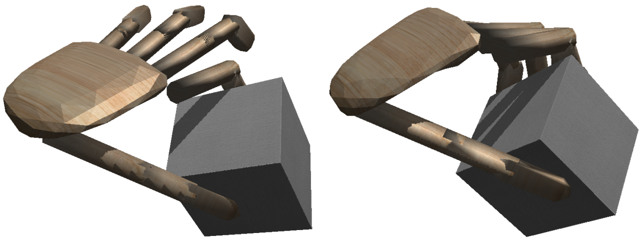


Fig. 4: Demonstrating the effect of adding the error summation term to the virtual coupling between the palms while picking up and then dropping a virtual object. The orange lines show the angular difference, $|\Delta Rot(t)|$, and position difference, $|\Delta Pos(t)|$, between the actual and the virtual palm using the additional summation term. The purple line shows the likewise data for the standard spring-damper coupling. For reference, we also plot the simultaneous linear, $|\vec{V}(t)|$, and angular, $|\vec{\omega}(t)|$, speed of the actual hand.

(a) Hand with a weak grip. (b) Hand with a strong grip.



(c) VR hand with a weak grip. (d) VR hand with a strong grip.

Fig. 5: A weak and a strong virtual grip and the corresponding actual hands.

the left and right arbitrarily without holding an object. As Fig. 3 demonstrates, the error summation term improves the position and rotation difference between the coupled palm. However, the effect is less noticeable than when the hand was steady because of the dynamic movements and change in the hand's acceleration. Finally, in the third movement, the hand is interacting with a virtual object. More precisely, the user's hand is initially hovering above an object, then they pick the object up and drops it after a moment (Fig. 4). At $t = 0$, the hand moves toward the object and has not picked it up yet. During this time, the position and rotation difference is less when the error summation term is active. However, just as the hand picks up the object, the standard coupling performs better for a tenth of a second. Afterward, as the user is holding the object, the modified coupling outperforms the standard coupling. However, at around $t = 1.4$, as the user is dropping the object, the modified coupling momentarily slightly underperform compared to the standard coupling in matching the rotations; but, it performs better in matching the positions. Finally, after the object is dropped, the modified couple quickly outperforms the standard coupling in reducing both position and rotation error.

Overall, our experiments show that adding the error summation term to the virtual coupling connecting the actual and virtual palms improves the co-location in most scenarios. The only period where it does not improve it, even slightly underperforms, is the moments where the hand comes in and out of contact with a virtual object.

3.3. Limitations

Using a physically-based virtual hand should give a sense of mass perception and allow mass discrimination between virtual objects. However, we suspect that this claim is stronger in some scenarios and weaker in others. While grasping and moving a light object, the spring-damper forces counteract the force of gravity and inertia on the object. Therefore, using our virtual hand, if a user grasps an object with a low virtual mass, they can easily pick it up and quickly move it around the workspace with high acceleration without it coming out of their grip. However, for a heavier object, the user can still pick it up, but they have to increase their effort, such as using more fingers for grasping or closing their grip further so spring-dampers would apply more force on the object (Fig. 5). Also, it is not possible to accelerate it as fast as lighter objects since the inertial forces are higher and can overcome the spring-dampers in the virtual hand and open the virtual grasp. Depending on the spring dampers' coefficients, after a certain point in mass, it would be really difficult or eventually impossible for the user to move or pick up the object. We hypothesize that the limit on how fast the user can accelerate the virtual object in hand and how challenging it is to pick it up gives the user a sense of the virtual object's mass and enable them to discriminate two objects based on their mass. However, using this technique, it is hard to perceive the difference in mass between two light objects (<1kg) since it would be almost effortless to pick both of them up off the ground and move them quickly without dropping them. To overcome this problem, we introduce a vibration feedback effect to complement our VR hand.

4. Vibrotactile Feedback

In day-to-day physical interactions with real-world objects, we can feel the object's mass and compare it to other heavier or lighter objects through our sense of touch. Virtual experiences that do not provide haptic feedback lack realism compared to real-world experiences. One of the modalities of haptic feedback is vibrotactile feedback in the form of mechanical waves or vibrations.

Our goal is to complement the VR hand in giving the user a perception of an object's mass by communicating the net force they apply to the object. To achieve this without limiting the hand and finger movements, we use one actuator to render our haptic feedback. We use sinusoidal vibration feedback with a frequency range between 100Hz and 150Hz, making it perceivable only by the Pacini mechanoreceptors in the fingertip skin. The Pacini mechanoreceptors cannot detect the direction of the mechanical waves; therefore, only one actuator is sufficient to render our haptic feedback in all directions.

4.1. Method

We strap a VCA (voice-coil actuator) to the fingertip of the index finger. We chose the index finger because it has a critical role in picking up objects with a pinch grasp. Other fingers, such as the thumb and the middle finger, can have an important role in grasping as well; However, attaching voice-coil actuators to multiple fingers limits the relative movement of fingertips and manual dexterity.

While a user grasps an object, we render the vibration feedback $O(t)$ with frequency $O(t)_F$. The amplitude of $O(t)$ is proportional to the object's mass M and acceleration $A(t)$. This results:

$$O(t) = \alpha M A(t) sin(2\pi t O(t)_F), \tag{5}$$

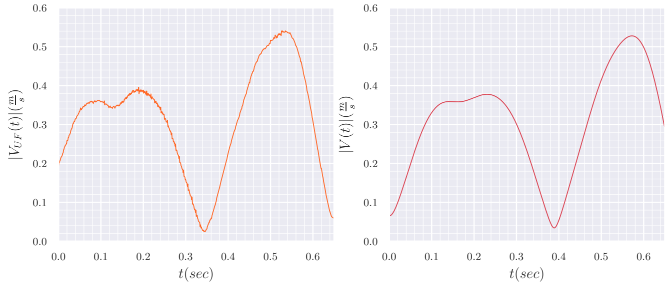


Fig. 6: The unfiltered velocity for a virtual object, $V_{UF}(t)$, versus its filtered velocity, $V(t)$, during a shaking movement.

where α is a scaling constant to control the range for the vibration energy perceived by the user. The vibration feedback should be only strong enough so that users can perceive the vibration when slowly moving the lightest weight in the scene. The value of α also depends on the hardware components of the haptic chain, such as the signal amplifier and the haptic actuator. For our setup, we set the α value in a way that, if the user accelerates a 1kg object at 1 g, the measured vibration at the fingertip is on average 0.32g, which allows users to perceive the vibration feedback when slowly moving the lightest weight (0.25kg) in our experiments. The frequency of the output signal $O(t)_F$ dynamically changes from 100Hz to 150Hz based on the velocity of the virtual object $V(t)$, that gives:

$$O(t)_F = max(150, 100\frac{|V(t)| + 2}{2}), \tag{6}$$

where at speeds near zero, the signal's frequency is 100Hz, and as the speed increases to about one m/s, it goes up to 150Hz. To ensure a smooth vibration signal, we apply a second-order Butterworth lowpass filter tuned to a sample rate of 1000Hz and corner frequency of 20Hz (i.e., -3db amplification at 20Hz) to the velocity data. We use the filter to calculate the low passed velocity of the virtual object, $V(t)$, based on its unfiltered velocity, $V_{UF}(t)$ (Fig. 6).

We set the signal's amplitude proportional to $MA(t)$ which, according to Newton's second law of motion, represents the net force acting on the virtual object. In our method, we ignore balanced or counteracted forces acting on an object since the counteracted forces from grasping can be similar between a light and a heavy object. As an example, we can grip a light object just as hard as a heavier one.

During a virtual experience, the voice-coil actuator is always strapped to the user's index fingertip. However, the vibration feedback renders only when the user's virtual hand grasps a virtual object and not during their free-hand motions in the scene. To detect if the user is grasping a virtual object, we check whether the virtual object is off the ground and touching the virtual hand's palm and the distal joint of the thumb, index, or middle finger. If grasping is detected, the vibration feedback is rendered for the user through the voice coil actuator.

Whenever the system detects that the user is no longer grasping a virtual object, the vibration feedback rendering stops. However, in a physical simulation, even when the user is grasping the object, the hand parts may momentarily lose contact with the virtual object for a few cycles, and this might cause on/off pulses in our vibration feedback. To avoid these impulse noises in our signal, we stop the vibration feedback after no grasping is detected for ten milliseconds.

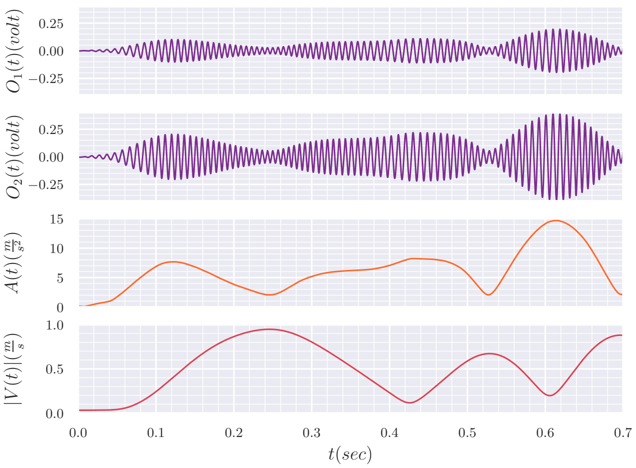


Fig. 7: The output voltage of the vibration feedback for two virtual objects with mass values 0.5kg, $O_1(t)$, and 1kg, $O_2(t)$, during an arbitrary shaking movement with acceleration, $A(t)$, and velocity $V(t)$.

4.2. *Vibration Feedback for Improving Mass Perception*

When the user picks two virtual objects with different mass values and moves them around the scene with the same motion, the vibration effect is more substantial for the heavier object than the lighter object, proportional to their mass difference. In other words, the user feels more energetic mechanical vibrations on their skin when interacting with a heavier object. We suspect users perceive these vibrations as a resistance force to acceleration (similar to the force of inertia), which leads them to perceive the mass of virtual objects.

The limitation of the physically-based hand is that if we take two light virtual objects such that one object is twice as heavy as the other, it would be difficult to perceive the mass difference since both masses are well within the threshold of what the virtual hand can grasp and move around in the VR scene. However, with the presented vibration feedback, the vibration at the user's skin for the heavier object has twice the amplitude (Fig. 7). As a result, we expect that the user perceives the mass difference between the objects based on the vibration feedback.

5. Evaluation

We evaluate our VR mass rendering techniques and verify our claims using both qualitative and quantitative measurements. We conducted a user study in which participants interact with virtual objects using the co-located virtual hand and perform several object manipulation and comparison tasks. Moreover, we study the effect of the proposed vibration feedback on participants' ability to perceive virtual objects' masses and compare them based on the heaviness. More specifically, we look to assess these two hypotheses in our evaluations:

- Grasping and manipulating virtual objects using a co-located physically-based hand model in virtual reality gives a sense of mass perception and allows some degree of mass discrimination between virtual objects.

- The proposed vibration feedback can improve the sense of mass perception and enhance mass discrimination precision during virtual interactions between a physically-based virtual hand and virtual objects.

To examine the validity of the first hypothesis, participants perform virtual tasks involving interactions with objects with different mass values using the VR hand. However, evaluating these results of the VR hand interactions is not enough to validate our first hypothesis. The virtual environment runs in a physics engine, and users might get other clues to detect the difference in mass between objects that are not from the VR hand interactions only. These clues include: how the object interacts with each other, how they bounce when dropped on the virtual ground, and the speed at which they fall in the presence of air friction. To control the experiment for these additional cues, we ask participants to interact with each object individually and not push or touch an object using another. Additionally, we add a control interaction mode to our platform, called the spherical cursor. In this mode, instead of a co-located hand, users only see a spherical cursor co-located with the center of their palms. If the spherical cursor is within an object and the user puts their hand in a grasp pose, that object follows the cursor around the virtual scene until the user opens their hand. During grasping using the spherical cursor, we move the object by applying force to it in the cursor's direction. However, this force is proportional to the object's mass. As a result, objects with different mass follow the cursor at the same speed and acceleration. Therefore, comparing the quantitative and qualitative results from user interactions using a physically-based hand versus the spherical cursor as a baseline allows us to validate the first hypothesis.

To test the second hypothesis, participants interact with virtual objects using the physically-based hand both with and without the vibration feedback, which allows us to compare the results and analyze the effectiveness of the vibrotactile feedback in mass perception and discrimination.

5.1. Setup

In this subsection, we describe the study setup's hardware and software components and the range of mass values we use for our virtual objects. We use the MMXC-HF VCA by Tactile Labs, a relatively compact tactile actuator ($36mm \times 9.5mm \times 9.5mm$), and the Tactile Labs QuadAmp multi-channel signal amplifier. A pair of thin wires attached the VCA to the signal amplifier placed on a nearby table. The cables from the actuator point outwards from the user's finger, limiting the chance of cables touching the user's hands during virtual interactions. Using a 3d printed mount, we attach the voice coil actuator to the user's index fingertip (Fig. 8). We use the PC-powered Oculus Rift as our VR interface, which allows for external PC-based graphical computation. For tracking the user's hands, we attach a Leap Motion controller on the front side of the Oculus Rift VR headset for hand tracking.

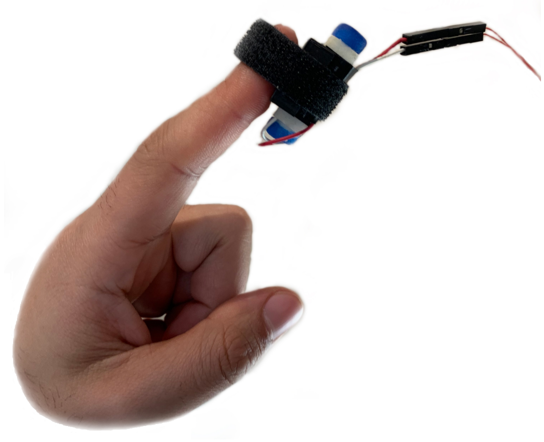


Fig. 8: The voice coil actuator is strapped to the index fingertip of the user's dominant hand

In our system, we use the Bullet physics simulation [38] as our physics engine. One desirable feature of the Bullet library is that it permits the virtual hand's control by applying virtual force and torque from an external source. This feature enables us to implement the virtual coupling between our virtual hand and the tracked hand.

To render the virtual scene to the VR headset and work with the Bullet physics simulation, we use the Chai3D library. Chai3D [39] is a platform-agnostic haptics, visualization, and interactive real-time simulation library. Moreover, it supports visualizing using the Oculus Rift headset and has built-in Bullet physics integration, making it ideal for immersive and physically realistic haptic experiences.

In our study, we use cubes as our virtual object's shape since they are easier to grasp. During our experiments, there may be multiple virtual cubes in the scene with different mass ranges. For setting the mass range in our experiments, we should consider the physics engine that we use. The Bullet physics engine recommends keeping the mass of objects around 1 kg and avoid very large or small values [40]. Therefore, during our preliminary experiments, we set the virtual coupling coefficients so that users could pick up virtual cubes with masses up to 4 kg. However, past that mass point, it becomes too difficult to pick up the virtual cubes. Since we expect users to be able to interact and pick up any virtual cube in the scene, we chose 2.5 kg as our upper mass limit in our user studies for the heaviest objects and 0.25kg as our lower mass limit for the lightest objects.

5.2. Safety Precautions

Due to the nature of the study, the use of custom hardware, software, and multiple VR and haptic devices, we decided to hold an in-person user study in which participants show up to the research lab. However, this study was conducted throughout the Fall of 2020 and Winter of 2021, which was during the Covid-19 pandemic. We took several steps to ensure the safety of the interviewer and the participants, including sanitizing surfaces and equipment in the study area, maintaining social dis-

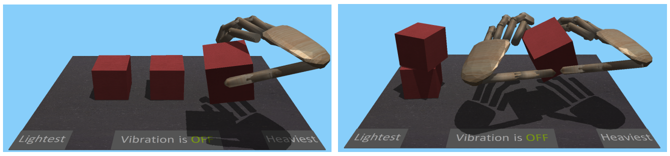


Fig. 9: Participants should only use their dominant hand (Left). Interaction using both hands (Right) is prohibited. Also, experimenting with interactions between objects, such as stacking them on top of each other, is forbidden.

Fig. 10: A participant interacting with a virtual object while wearing the VR headset with the Leap Motion hand tracker, VCA and noise-canceling headphones.

tancing and wearing masks at all times, and providing disposable gloves and VR face masks to the participants.

5.3. Participants

Ten participants (5 female, 5 male) took part in this study. All participants were right-handed. Half of the participants were 18 to 25 years old, and the other half were in the age range of 26 to 35. Three participants had never used VR headsets before; one participant used them few times per week and the rest at most a few times per year. Seven of them had interacted with virtual objects during their VR experiences, and three had used haptic devices in VR games and applications. This study was held at the University of Calgary's main campus. All of the participants were either graduates or studying at faculties of science or engineering at the University of Calgary and were recruited through word of mouth. Nine participants had either a master's or doctorate degree or were currently graduate students. This study was approved by the University of Calgary Conjoint Faculties Research Ethics Board (REB18-0708). Participants received 20$ compensation for taking part in this user study.

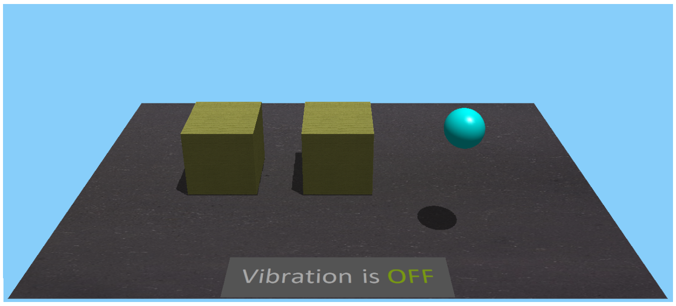


Fig. 11: Two virtual cubes with random weights are placed in front of the participant to compare. The co-located spherical cursor mode is active, and the ”Vibration Off” label indicates to the participant that they should not expect any vibration from the voice-coil actuator.

5.4. Study

We begin the study by spending a few minutes (<8) familiarizing the participants with the VR headset, Leap Motion hand tracker, and the virtual study environment. After placing the haptic actuator on their dominant hand's fingertip, they practice how to pick up and move a virtual cube (1.25 kilograms) using the virtual co-located hand. We ask participants to always use their index fingers in grasping since the haptic actuator is attached to it. They are also encouraged to engage more fingers or tighten their grip to increase the grasping strength and move the training object around the scene both slowly and quickly. For consistency, we ask the participants only to use their dominant hand to interact with the virtual elements in the scene when the tasks start (Fig. 9). During the virtual tasks, participants wear active noise-canceling headphones while white noise is played through them to block any audible signal from the haptic actuator (Fig. 10).

In the first task, we present participants with six pairs of cubes and ask them to interact, grasp, move the objects, and think aloud about the experience. Furthermore, we ask them to compare the two cubes based on their mass and say if they feel they have the same mass or if one is slightly or considerably (or to whatever degree they perceive it) heavier than the other. Participants interact with virtual objects using the three interaction modes in the following order: spherical cursor, virtual hand without the vibration feedback, and virtual hand with the vibration feedback. As an example, Fig. 11 shows this task's setup while the interaction mode is set to the spherical cursor. For each interaction mode, participants compare two pairs of cubes. One pair has the largest mass difference given our mass range (0.25 and 2.5 kg), and the other pair has a smaller mass difference (0.25 and 0.5 kg). The system randomly decides if the smaller or larger mass difference pair is first presented to the user and randomly places the two cubes with similar appearances on the table for each set to avoid learning from the previous rounds.

In the next part, we ask participants to sort virtual cubes based on their mass. In sorting, a higher number of objects to sort means the participant spends more time picking up and moving objects around the scene, which results in a fuller user experience in comparing weights. However, a higher number of objects to sort increases the average time to complete the task,

Fig. 12: Three virtual cubes with random weights are placed in front of the participant to sort in ascending order from left to right. The ”Vibration On” label indicates to the participant that they should expect vibration from the voice-coil actuator when picking up objects.

limiting the number of sorting rounds users can perform during a study session. Our preliminary experiments concluded that three cubes could offer a reasonable balance between sorting time and user interaction with objects.

We quantized our mass range (0.25kg to 2.5kg) into two weight sets of size three. Having more than one weight-set allows a more in-depth analysis of the interaction modes across our mass range. Weber's law states that the difference in magnitude needed to discriminate between a base stimulus and other stimuli increases proportionally to the intensity of the base stimulus [41]. We can easily differentiate a 0.5kg mass versus a 1kg mass, but it is harder to distinguish a 10kg mass from a 10.5kg even though both pairs have the same weight difference. Therefore we chose our mass values with equal ratios between them using a geometric series. That gives a light weight-set (0.25kg, 0.44kg, 0.79kg) and a heavy weight-set (0.79kg, 1.4kg, 2.5kg).

Participants sort random permutations of the light and the heavy weight-set, using the three different interaction modes (spherical cursor, virtual hand without vibration feedback, the virtual hand with vibration feedback). Therefore we have six modes of sorting. As an example, Fig. 12 shows this task's setup while the interaction mode is set to the virtual hand with vibration feedback. In all sorting modes, three virtual cubes with similar appearances are placed on a virtual surface, and participants have to place them from left to right in ascending order based on the perceived mass. Participants perform six rounds of sorting for each mode. During each round, sorting modes are ordered randomly to remove the learning effect between the modes. Before the sorting task begins, we rotate between the modes to familiarize the participant with the scene. Furthermore, we ask participants to grasp each object at least once before finalizing their decision. Also, we recommend keeping each sorting under a minute; however, this is not a hard limit.

When the sorting task finishes, participants fill out a questionnaire regarding their experience during the two virtual tasks. After participants fill out the questionnaire, we ask them to elaborate on their answers during a semi-structured interview. Our post-session questionnaire is as follows: (each question is repeated for each of the interaction modes)

- While interacting with objects, I could perceive their mass. 1 to 5 (Strongly Disagree, Disagree, Neutral, Agree, Strongly Agree)
- I could feel one cube was heavier than the other. 1 to 5 (Strongly Disagree, Disagree, Neutral, Agree, Strongly Agree)
- How was your confidence level in sorting objects? 1 to 5 (Not confident at All, , , , Very Confident)
- How realistic were the interactions with objects? 1 to 5 (Very Unrealistic, Unrealistic, Neutral, Realistic, Very Realistic)
- Would you recommend experiencing the “” in VR games during interactions with virtual objects? 1 to 5 (Do Not Recommend at All, , Neutral, , Highly Recommend)

An overview of the user study procedure and tasks is shown in Fig 14.

5.5. Results

We show the sorting results of the six different sorting modes in the form of confusion matrices (Fig. 13). The matrices' diagonals show the number of times the objects were sorted correctly. Moreover, each row in a matrix shows how participants sorted each weight. For example, the middle matrix in the bottom row of matrices shows the sorting results for the heavy-weight set using the virtual hand with no vibration feedback. Furthermore, the bottom row of that matrix demonstrates that 33 times the heaviest weight in the set was placed correctly, 18 times it was chosen as the medium weight, and 9 times it was ordered as the lightest weight in the set. Using the non-parametric Kruskal-Wallis test, we analyze the statistical significance of the difference between placement distributions of light, medium, and heavy objects for each of the sorting modes. For the spherical cursor (control mode), we observe statistically insignificant p-values of 0.463 for the heavy weight-set and 0.800 for the light weight-set, showing that the user could not discriminate between weights in this mode. For the virtual hand with no vibration feedback, we see statistically insignificant results for the light weight-set (p-value 0.928). However, for the heavy set, we see a significant effect of the virtual hand on sorting (p-value <0.001). In the case of sorting using the virtual hand with vibration feedback, we see a significant effect on sorting both for the light (p-value <0.001) and heavy (p-value <0.001) weight sets.

To check the validation of the first hypothesis, we see a significant improvement for the heavy weight-set compared to the control mode (spherical cursor). However, the same cannot be said for the light weight-set. To check for the second hypothesis, we see a statistically significant improvement in the light weight-set with the vibration feedback compared to only using the virtual hand. However, for the heavy set, we see significant effects both from virtual hand with and without the vibration feedback. Therefore, to check if the observed improvements in the precision of sorting for the light, medium and heavy objects are significant, we perform row by row comparison between the two confusion matrices using the Wilcoxon rank-sum test. Comparing the number of correct sorts for the heavy weight (54 correct sorts versus 33) gives a statistically significant p-value of <0.001 (effect size 0.8449), for the medium weight (44 correct sorts versus 25) p-value is <0.001 (effect size 0.6705), and

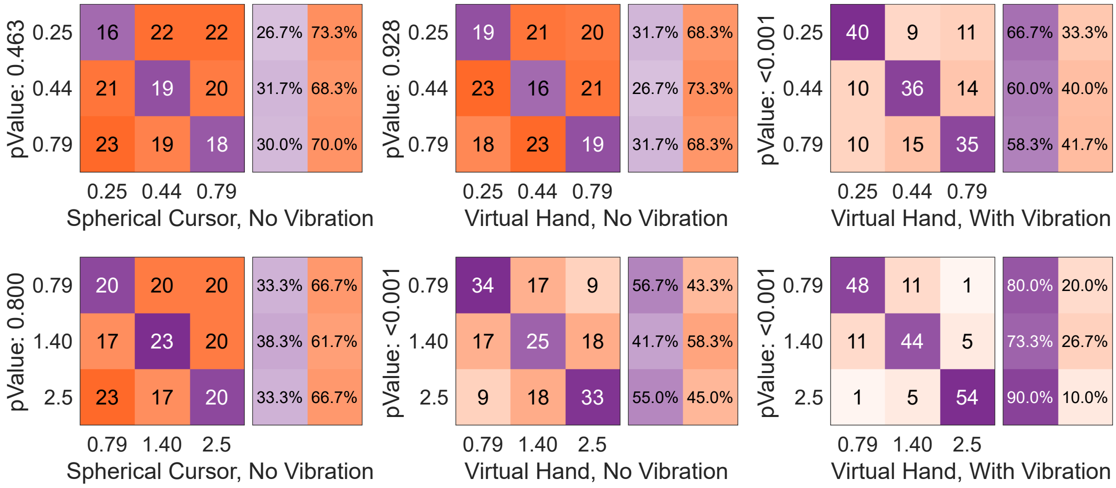


Fig. 13: The top three matrices show the sorting results for the light weight-set (0.25kg, 0.44kg, 0.79kg), and the bottom three show the sorting results for the heavy weight-set (0.79kg, 1.4kg, 2.5kg). From left to right, matrices represent the three interaction modes (spherical cursor, virtual hand with no vibration, virtual hand with vibration).

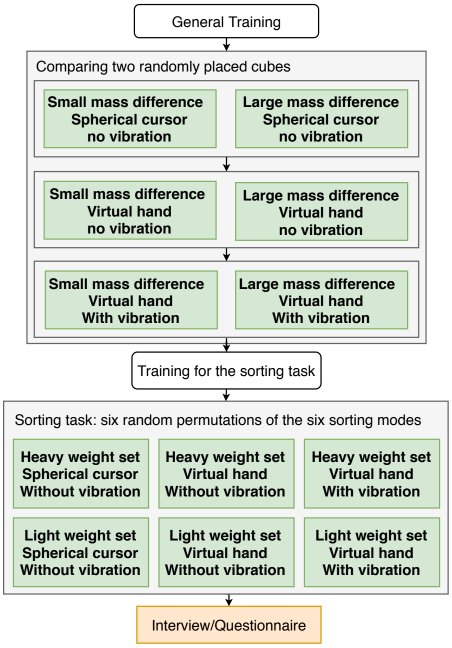


Fig. 14: The order and description of tasks in our user study.

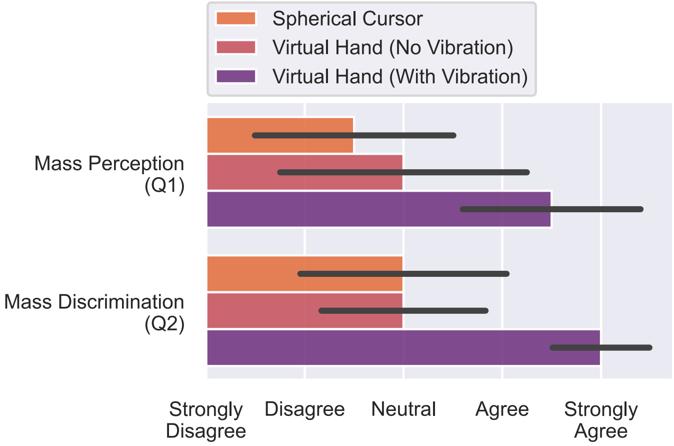


Fig. 15: Users compare the sense of mass perception and discrimination between the three interaction modes in the post-session questionnaire. The bars represent the mean answer, and the black lines show the standard deviation.

for the light weight (48 correct sorts versus 34) p-value is <0.01 (effect size 0.5138), which shows that for the heavy weight-set the vibration feedback improvement is statistically significant as well.

The results of the questionnaire in Fig. 15 show that participants declared an improvement in mass perception and discrimination when the vibration feedback was enabled compare to only using the virtual hand. P6 (Participant #6) mentioned "With the hand no vibration, it was harder to tell the difference in mass, but I think you could still, it was realistic enough that it was engaging, but the vibration one I'm not if it's like a mental thing, it just helps a lot more with the differentiating between the different masses and the movements". We also see neutral results for the spherical cursor. Generally, participants mentioned they could not differentiate between the objects using the spherical cursor. P2 mentioned, "It was harder for me to use the cursor to compare the weights, most of the time I thought they were like identical". For the virtual hand without the vibration feedback, participants on average expressed neu-

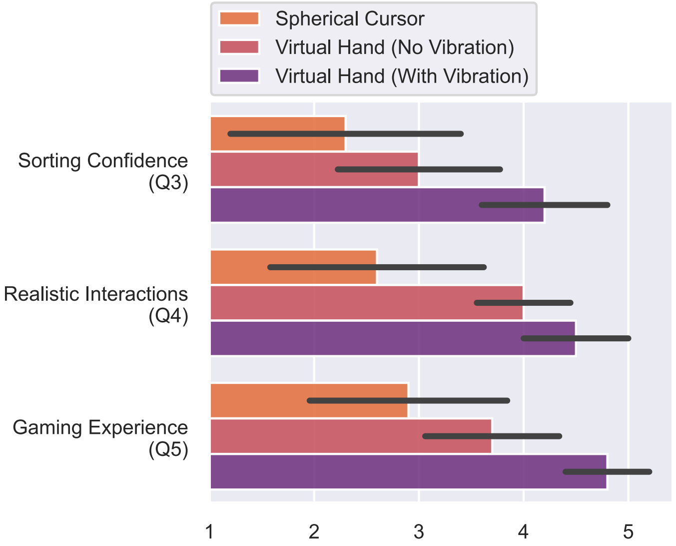


Fig. 16: Users compare the sorting confidence, sense of realism, and gaming experience between the three interaction modes in the post-session questionnaire. The bars represent the mean answer, and the black lines show the standard deviation.

tral opinions regarding its ability to give them the sense of mass perception and discrimination. However, the results from the sorting task show they performed better than the control. Also, some participants mentioned different encounters that enabled them to differentiate between weights. P5 mentioned "I'm picking it up, how long would it slide, ok hold it, I shake it around it slides faster ... if I hold it, it slips faster then it's heavier", and P6 said "(with the virtual hand) if I grab it loose the heavy one just drops as opposed to the light one stays in even if I'm shaking it", and "looking at the movement, if I'm moving my hand it's a bit slower it just feels heavier versus if it's a quick it just feels lighter"

Fig. 16 shows that participants expressed having more confidence in sorting when the vibration feedback was enabled. However, without the vibration feedback, they expressed neutral confidence. Furthermore, participants generally stated that the vibration feedback added to the interaction's realism and that the virtual hand's interactions were realistic. P4 said "For the vibration also, I felt like it helped me, felt like it's more real, I'm touching things, not just I'm seeing that I'm touching things". Furthermore, participants expressed interest in experiencing the vibration effect in virtual reality games.

Finally, we asked the participants how did interaction with virtual objects feel when they vibrated. P2 said: "if felt like it has resistancy to move, based on that I felt like it's heavier, might be heavier" and P7 mentioned "When I picked a cube with vibration, I could feel that something is trying to, I don't know, annoy me bother me, might be something like the gravity taking it back to the ground, it feels that I should put more energy to pick it up" and further elaborated "the one that without vibration I just pick it with two fingers I played with that, but the one with vibration when I tried to pick it with two fingers, suddenly I tried to keep it with all my fingers because I thought that it might slides and drops."

Overall our findings indicate that the presence of the physically-based virtual hand both with and without the vibration effect gives a sense of weight discrimination and perception. However, the virtual hand without vibration feedback is only effective for heavier objects closer to the hand strength threshold. Furthermore, the virtual hand with the vibration effect improves the weight perception and discrimination sense for both lighter and heavier objects without having a negative effect on the realism of the experience. Therefore, our results validate our hypotheses.

6. Conclusion

Virtual reality offers highly immersive simulated experiences with a high sense of presence. However, objects in VR do not have real masses; hence it is difficult to sense their weight. Humans rely on both visual and tactile feedback to sense the mass of objects. In order to enable users to perceive the mass of virtual objects in VR, researchers have proposed various methods that provide visual or tactile feedback to the users. However, rendering the mass of objects in virtual reality without limiting hand movements and realistic interactions is a challenging task. In this paper, we propose using a physically-based hand in VR to give a sense of mass perception and discrimination by enabling physically realistic hand-object interactions. The physically-based hand uses virtual spring-dampers to connect the corresponding parts between the user's actual and virtual hands. We improve the co-location between the actual and the virtual hand by introducing an error summation term to the palm's virtual coupling and showing that it outperforms the normal spring-damper in most scenarios. However, when the hand comes in and out of contact with virtual objects, our modified coupling can underperform compared to the traditional spring-damper.

To improve the mass rendering abilities of the physically-based hand, We propose a complementary vibration effect proportional to the object's mass and acceleration, or the net force acting on the object. When the user grasps a virtual object, the vibration renders at the fingertip, and its frequency modulates based on the object's velocity.

To test our hypotheses, we conducted a user study and performed qualitative and quantitative analyses. In our user study, participants performed multiple rounds of object interaction and comparison tasks using three different interaction modes: a spherical cursor (control mode), the virtual hand with no vibration, and the virtual hand with vibration. Our results indicated that the physically-based virtual hand gives a sense of mass perception and discrimination for heavier objects closer to the upper limit of its grasping strength. Furthermore, the vibration feedback dramatically enhances users' mass perception and discrimination abilities for a broader mass range. Participants also reported that with the addition of the vibration feedback, they had more confidence in sorting objects and that the interactions were more realistic compared to only using the physically-based hand.

7. Future works

We propose several directions of future work for this paper. One potential future direction is to perform a more comprehensive analysis of the mass discrimination abilities of users when using the physically-based virtual hand and the vibration effect for a broader mass range and different mass ratios between the objects. Furthermore, calculating the probability that a user notices a weight difference between two given objects with different known mass values. Moreover, we are interested in analyzing the behavioral effects of the physically-based hand and vibration feedback, such as the mean acceleration and velocity of the users' hand during interactions or the duration and number of times users grasp objects of different mass values.

Another potential future research is analyzing the mass rendering abilities of the physically-based hand and vibration feedback during bi-manual interactions, such as working with large objects that need both hands to control or passing objects between the hands. Using two physically-based hands could potentially provide additional mass feedback to the user. Moreover, using two hands requires investigation of design decisions regarding the vibration rendering, such as if the intensity of vibration should split between the two hands or remain the same.

In this paper, we only use a single vibration actuator to render the mass of an object. One valuable research question is whether it is worth adding more actuators to other fingertips, phalanges, or the palm at the cost of increasing the complexity and limiting the finger and hand movements. However, such additions could potentially provide more feedback for dextrous actions such as continuously rotating an object in hand.

Another direction of future work is examining the combination of our vibration feedback for mass rendering with other tactile haptic feedback such as texture rendering. Since these effects are both based on rendering mechanical vibration, it is sensible to use the same actuator to render both. However, the question is how can we render the two effects so that the user does not misperceive one as the other.

In this work, we study the mass rendering abilities of the sinusoid vibration feedback while added to a physically-based virtual hand. Future investigations can combine the vibration feedback with other interaction techniques such as hand-held VR controllers or gesture-based approaches.

Finally, investigating the effects of our mass rendering method on users' efficiency, accuracy, and sense of presence in a particular use case such as virtual object assembly or VR training for a physical task would be valuable.

8. Acknowledgements

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