HapticCollider: Ungrounded Force Feedback for Rigid Collisions during Virtual Tool Use

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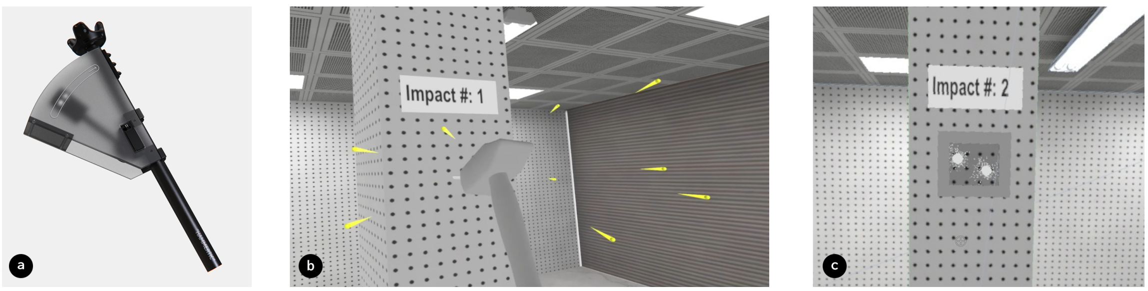

Fig. 1. a) The current version of HapticCollider was represented in compliance with the requirements obtained during the design phase before assembling the real version. b) HapticCollider's virtual representation hits a nail in a virtual world set in a workshop. c) A broken glass is shown after two hammer hits using HapticCollider.

Controllers are not merely the dominant interface to interact in virtual reality (VR); they also are the main resource for haptically perceiving the virtual world. As standard VR controllers fail in generating realistic haptic feedback, we designed HapticCollider, a kinetic controller rendering force feedback, e.g., to simulate a collision when hammering or hitting against a virtual object. In our user study, we demonstrated that HapticCollider significantly increases realism in tool usage compared with a standard VR controller. As key factors for tool use realism in VR, we identified force feedback, controller weight, and grip shape in combination with software solutions, namely collision prediction, and control-display ratio to render the force timing, as well as, the tool position according to the user's expectations.

CCS Concepts: • **Human-centered computing → Mixed / augmented reality**; *Empirical studies in interaction design.*

Additional Key Words and Phrases: haptic feedback, force feedback, rigid collision, ungrounded, virtual reality, tools, proprioception

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1 INTRODUCTION

Haptic feedback enriches interactive applications of various domains, such as education [30], training [21, 32], robot-assisted surgery [15, 25], limb prostheses [6, 23], and pain reduction [44]. It is perceived through haptic perception, which includes a variety of sub-modalities, for example, the perception of skin vibrations, pressure, pain, temperature as well as kinesthesia [17]. While through these haptic sub-modalities, we are able to recognize a rich bandwidth of physical properties, such as roughness, pressure, and proprioceptive stimuli such as weight and force, common haptic output technology does not cover the sensory bandwidth humans theoretically can perceive. For example, state-of-the-art VR controllers, such as Oculus Quest or HTC Vive, only provide haptic feedback by vibrotactile actuators, which limits the haptic experience in VR.

To reduce that research gap, researchers looked into how to design VR controllers that provide other haptic feedback than vibration. Drag:on, for example, can render a shovel by changing the controller shape [45], and ElastOscillation can render shaking elastic activities, such as bartender-cocktail shaking or fishing, using a motor-controlled mass located on the top of a standard VR controller [39].

Force and weight, the haptic sub-modalities on which this work focuses on, have also been a goal of human-computer interaction (HCI) research. For example, Air Racket [38] uses compressed air to generate force feedback from hitting balls in VR sports rackets. White et al. [41] investigated how to render a heavy tool like a baseball bat in VR and found that matching tool weights is important to increase realism. In addition, the researchers recognized that supplying force feedback for heavy tools, can present difficulties since the efficacy of vibrotactile feedback reduces as the weight of the device increases. In this regard, it remains unclear how to integrate force feedback into a weighted proxy in virtual reality to generate realistic haptic feedback, which we address in this work.

While these works augmented the users, which might lack usability, there is no VR controller solution that renders realistic impact force feedback using a weighted tool for VR. To reduce that research gap, we present HapticCollider, a VR controller that lets users perceive collisions through ungrounded force feedback when hitting virtual objects with a weighted tool. HapticCollider has the potential to simulate and improve realism of various actions in VR which rely on a weighted tool, such as hammering objects (see Figure 1 b) and hitting a baseball, but it could also be build as a more lightweight version to represent virtual tasks, such as fishing, drumming, and table tennis.

Beside showing that HapticCollider is significantly more realistic than a standard VR controller, we identified parameters that matter in collision realism experience design, such as the force itself, but also the controllers' weight and shape. We conclude with design recommendations for building ungrounded force feedback controllers, through which we hope to make VR more realistic and enrich its haptic experience.

2 RELATED WORK

Aiming at making virtual tool use more realistic through haptic feedback, we first discuss why and how realistic haptic feedback is used in VR. Then we look at previous work on haptic controllers in VR in general, and lastly, as we are particularly interested in force feedback, we discuss related work at the end of this chapter.

2.1 Realistic Haptic Feedback for VR

When interacting with a system, the resulting user experience is the user's perception created by multiple stimuli generated by the system [16]. In VR, this is related to the concept of immersion, defined as the extent to which the user feels present in a virtual environment [31]. Thereby, haptic feedback in VR is generated to simulate physical responses from a virtual world through sensations, and as consequence, increasing immersion and realism [22]. Thus, it is relevant to generate realistic haptic feedback, which refers to the ability to generate accurate haptic feedback consistent with previous experiences that users have had in the real world.

To guarantee realistic haptic feedback, Muender et al. coined the concept of Haptic Fidelity [22]. The following three components described by Muender et al. are of particular interest for our aim of designing a novel VR controller that provides force feedback: *Sensing*, *Hardware*, and *Software*.

Sensing refers to the degree to which the system can stimulate the haptic receptor on the human body to render natural haptic feedback. Considering that the human body has different haptic receptors that allow to perceive and distinguish different haptic stimuli [17], it is relevant to match the body location, area extent, stimuli type, and magnitude of haptic feedback that is rendered, being consistent with previous experiences in the real world.

In the context of the *Hardware* component our focus lies on the subcomponent called *Hardware Latency* due to its relevance to our equipment. *Hardware Latency* refers to the potential delay in haptic feedback caused by the performance of the hardware. Specifically, haptic devices are assembled from mechanical components and software solutions that necessarily originate delays in executing algorithms and transmitting the signals. Regarding the perception of this latency by the users, there is evidence that shows that users can perceive a delay of 25ms or above while using haptic devices [12]. This fact could negatively affect the experience since the user could not adequately integrate the haptic feedback into the other stimuli and, thus, destroy realism.

The *Software* component involves the utilization of algorithms and programming techniques to regulate haptic sensations. For instance, prediction algorithms can be employed to anticipate events and trigger haptic feedback in advance, mitigating latency issues and maintaining a realistic experience.

When designing HapticCollider, we learned from previous work to aim at a high level of sensing, which we measure through realism, integrate a prediction algorithm to reduce latency, and mimic the tool's use in VR, similar to how the tool would be used in reality.

Haptics in VR has been recognized as a valuable resource for improving training, evidenced by its ability to enhance psychomotor skills, reduce learning curves, and increase precision in the use of surgical instruments [26]. HapticCollider, in particular, has the potential to improve the realism of virtual training by providing impact force feedback for a variety of tools. To meet specific training needs, HapticCollider's haptic properties, such as weight and force output, can be adapted. For instance, HapticCollider could be used in virtual fire rescue training scenarios [14], such as breaking down doors, or in archaeology training for excavating a Bronze Age settlement [8] as well as for instrument learning applications [9].

2.2 VR Controllers for Enriched Haptic Feedback

As we developed a VR controller with enriched haptic feedback, research on novel controllers that provide haptic feedback other than vibration is highly mesmerizing.

Drag:on [45] is a VR controller based on a handheld fan design that allows shape-changing dynamically by opening or closing its structure, and thus, rendering air resistance to simulate a shovel while it is dragged into the air. Shifty [46] is a VR controller that can render different weights using a mass that changes its location inside a long handle as if it were a sword. In addition, ElastOscillation [39] regulates the elasticity of the bands that support a mass through a motor-powered mechanism. Thus, when the users agitate the VR controller, the mass moves in the range the elastic bands allow. Thereby, ElastOscillation can render a range of oscillating haptic feedback to simulate scenarios, such as bartender-cocktail shaking, fishing, wine-swirling, and pan-flipping. HapLinkage [18] is a prototyping framework that facilitates the construction of hand tools for VR. This framework uses linkage to simulate the mechanism of tools, showing simultaneously a visual representation of them in the virtual environment. The authors have built a bundle of examples such as a coffee grinder, stick shift, injector, medicine roller, scissors, spring pliers, spray bottle, paper trimmer, and a saw.

2.3 Force Feedback

To simulate a collision between a virtual tool and a virtual object using a VR controller, it is necessary to generate force feedback, e.g., when hammering a nail. In this direction, some researchers have developed VR controllers to generate force feedback using different mechanisms, as follows.

CLAW is a controller that simulates bullet shooting by moving the index finger using a servo motor [5]. JetController is a controller that simulates high-speed bullet shooting by a high-pressure pneumatic system [40]. Similarly, AirRacket can render realistic haptic feedback of playing with sport racquets by using compressed air propulsion jets [38]. Wireality is a string-guided device that can generate a full resistance to the hand by controlling the distance of the string that it is synchronized with the virtual environment by a servo motor located over the user's shoulder [7].

Electrical Muscle Stimulation (EMS) is a technology that induces power into muscles able to yield a limp motion or a limb muscle contraction, which can be perceived as force feedback. Such technique is used to simulate a repulsion of walls or boxes [20]. Another application of EMS is Impacto [19], it is a device that simulates hitting others and also being hit through the combination of two technologies, EMS and solenoid. It is used in the context of contact sports, e.g., boxing, where players are often being hit, and also hit other players.

The air has been used as a means of resistance to propel fans or drones and, as a result, generates force feedback in multiple haptic controllers. For instance, Flyable is a quadcopter-based controller that can fly and dynamically place a joystick where and when the virtual experience requires it or not [1]. Another example is Aero-plane, which is a controller that can change the centre of mass of a table by affecting the tilt angle using two jet-propellers [13]. Similarly, Thor's Hammer uses a propeller propulsion system of 6 motors to simulate the haptic feedback of a stick in 3-DOF that can perceive the water, herding a sheep, push buttons with different stiffness, and feel the gravity on different planets [11].

Previous work on VR controllers generated force feedback using a pneumatic system, finger relocation, propelled propulsion, strings, or EMS, capable of generating resistance stimuli to simulate weight change of tools, boxing kicks, or a ball hitting with racquets. However, there is no controller using an ungrounded and embedded mechanism able to render collision feedback of two rigid objects. To fill this gap, HapticCollider is an ungrounded VR controller with a fully integrated mechanism capable of generating collision feedback of two rigid objects without the need for any external apparatus, which makes it more realistic to be transferred into a product design one day. Consequently, our HapticCollider mechanism can generate a collision force against the handheld controller, such as it occurs in the real world when hammering a solid object with a tool.

3 FORCE FEEDBACK DESIGN & HAPTICCOLLIDER IMPLEMENTATION

To design force feedback provided to simulate the moment a user collides with a virtual object has the following key challenge: While in the physical world, the physicality of the object, e.g., a wall, would immediately stop the tool's movement, e.g., a hammer swinging hand, a state-of-the-art VR controller would never directly stop the user's hand at a collision. State-of-the-Art controllers embed vibrotactile actors that can inform the user about a collision, but they neither stop nor decrease the motion of the user's arm using haptic feedback. However, it has been shown that control-display ratio, which is a technique of displaying, for example, the arm position in VR at a different position than it is in the physical world, can influence where the user thinks their arm is and also influence where they move it [2]. Thus, to a certain extent, we could manipulate a user so that they slow down an arm motion after a collision or make them believe that their arm motion stops using visual feedback only. As activating the force feedback at the moment a collision is seen in VR causes some system delay, which would dramatically decrease realism [43], we implemented a collision-prediction algorithm that allows us to provide force feedback at the same moment the collision is experienced. How we implemented the combination of physical force feedback and control display ratio provided at the exactly same moment, identified through collision prediction, is described in the following:

3.1 Force Feedback

HapticCollider is a VR controller capable of realistically simulating the haptic feedback of hammering a nail, without having a physical nail counterpart in the physical world. To render a haptic experience of collision, we implemented force feedback using a kinetic mechanism. This mechanism hits a mass against the controller grip and in the opposite direction of the controller movement to work against the controller's motion once a collision between the hammer (represented by the controller) and a virtual nail is detected.

The HapticCollider hardware was built using an Arduino Uno working as an interface between Unity and the servomotor that releases the hit mechanism, see Figure 2. We further used a servomotor of the model Hitec HSB-9380TH as it is a powerful servomotor with a 34kg/cm torque. This servomotor was powered by 9.0V and 2.0A to facilitate the movement of the 394-gram hammerhead against the wooden handle, which is made from a deconstructed real hammer and has an oval shape. In order to attach the servomotor to the handle, a designed bracket was created using 3D printing. Similarly, a shroud was designed in 3D and assembled to HapticCollider in order to protect participants from being hurt by its mechanism. For stability during operation, six rubber bands were employed to securely hold the mass at the stated angle, while a lever supports the displacement of the mass by the servomotor. Finally, a HTC Vive tracker was mounted on top of the controller to track the controller's position. In total, the HapticCollider controller has a weigh of 1044 grams, which is heavier than a standard VR controller that has a weigh of 205 grams, but much closer to the weight of a steel hammer, which is about 900 grams.

It is worth noting that after every collision, a cooldown period is required to return the mass to its initial position. This cooldown phase takes approximately 621 ms. During this time, the servomotor moves the mass slowly to intentionally avoid any unintended force feedback that might interfere with the user's experience.

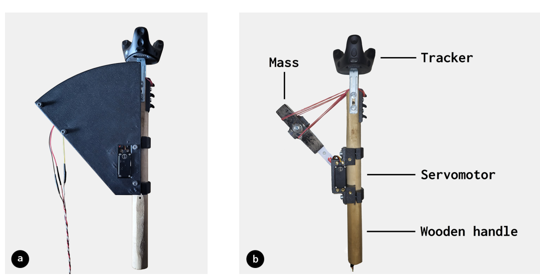

Fig. 2. a) HapticCollider is shown wearing shrouds to protect the participants. b) The parts of the HapticCollider mechanism are shown.

3.2 Collision Prediction

The iterative development process of HapticCollider involved a series of continuous refinements to achieve optimal performance and user experience. Through extensive testing of the initial prototype, we identified a delay between the virtual impact and the force feedback perceived through the HapticCollider grip. This approximately 350 ms delay is caused by the time it takes from detecting the virtual collision until the moment the mass was moved from its resting position towards the hammer grip, which it hit. As the delay dramatically decreased the realism of the scene, we implemented a prediction algorithm that can detect the collision before it happens.

This algorithm was implemented in Unity, and it is able to predict an impact from the hammer to the nail, by fulfilling the three criteria. Firstly, the hammerhead is moving towards the nail location, which is detected by the yellow ray and its red box as it is described in Figure 3 a). Secondly, the hammer speed is greater than a threshold that was found by doing small pre-studies. Lastly, the distance reaches a threshold that was found by doing small pre-studies. These threshold values were carefully defined based on the user experience observed during the pre-studies. The objective was to ensure that the visual feedback and the haptic feedback were synchronized, creating a cohesive user experience. By collecting feedback from users and analyzing their perception, we were able to determine threshold values that consistently aligned with their expectations. When these criteria are fulfilled means that the hitting is imminent and this triggers the algorithm sending an instruction from Unity to the servomotor generating the force feedback on time. When the virtual hammer hits the nail, shown in Figure 3 b), also triggers the control-display ratio process as it is described below.

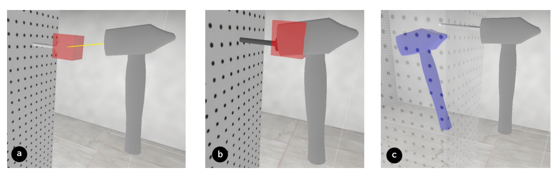

Fig. 3. a) Phase 1: The collision prediction algorithm is using the yellow ray with a red cube on the top, to anticipate the place where the hammer would hit the nail, in the event that the hammer movement is towards the nail. The yellow ray and the red cube are invisible to the participants. b) Phase 2: The hammer hits the nail. c) Phase 3: Control-display ratio acts through stopping the virtual hammer (gray) while the physical hammer (blue) goes further.

3.3 Control-Display Ratio

Since the force feedback is strong enough to considerably slow down the arm motion, but not to immediately stop it, we additionally use control-display ratio to freeze the virtual arm position where the collision happened, shown in Figure 3 c). As the user would still move the arm a bit further after the impact, the virtual hammer would move inside the virtual wall. Similar to previous work [2], we used control-display ration to re-target the position of the virtual hammer. We froze the virtual tool's position straight way after the virtual collision. Vice versa, when HapticCollider goes back and reaches the froze hammer in the hitting point, the user can recover the control and see the virtual hammer mapping the location and orientation of HapticCollider.

4 METHOD

In this section, we present the details of our experiment, aiming to evaluate the degree of realism achieved by HapticCollider when compared to a standard VR controller during a hammering task within a virtual environment.

4.1 Experiment Design

Our study implemented a 2x2 within-subject design, in which we defined the two independent variables controller (HapticCollider and a standard VR controller) and task (hammering a nail and smashing a glass). The levels of the variable controller were chosen to compare the proposed HapticCollider with state-of-the-art technology. The levels of tasks were chosen to investigate if the collision feedback works for precise and light hits (nailing) as well as for strong and powerful hits (smashing something, like glass). Thus, we aim to understand if our proposed feedback design potentially scales across applications and use cases. The dependent variable was Realism, which is a key aspect of usable VR and which was defined by the measure of the following concepts: Comparable Experience, Perceived Realism, Plausible Interaction, Influence, Real Objects, and Resistance.

4.2 Measurements

The questions related to the first three subscales Comparable Experience, Perceived Realism and Plausible Interaction were adopted from the *Reality Judgement and Presence Questionnaire* [3]. These subscales were also employed in a previous study [34], where an additional subscale called Comparable Forces was employed to compare virtual experiences with pre-exposure experiences using real tools. However, considering that our study investigates whether HapticCollider is more realistic than a standard VR controller, we excluded the Comparable Forces subscale. The three selected items are using a 7-point Likert Scale to score the perception given by participants, where the rating 1 is allocated to "not at all" and 7 is allocated to "completely".

- Q1. Comparable experience: To what extent what you experienced in the virtual world was congruent to other experiences in the real world?
- Q2. Perceived realism: To what extent did the experience seem real to you?
- Q3. Plausible interaction: To what extent did your interactions with the virtual world seem natural to you, like in the real world?

Furthermore, we adopted three additional subscales from the questionnaire of Rietzler et al. [27], which also was employed in a second study of these authors [28] to measure immersion in VR through pseudo-haptic feedback and muscle input. This questionnaire employed two subscales which we did not use: Realism and Like. As the subscale Realism was already employed in our study and due to the fact the subscale Like was found a subjective subscale that does not match with the aim of our study, we decided to omit these two subscales. The questions Q4 – Q6 were answered in a 6-point Likert Scale, where the rating 1 is assigned to "strongly disagree" and 6 is assigned to "strongly agree". The wording of these three questions are shown below:

- Q4. Influence: I could influence the behavior of objects with my actions.
- Q5. Real objects: I had the feeling of manipulating real objects.
- Q6. Resistance: I could feel a resistance.

In addition, we defined a semi-structured questionnaire with two questions to examine how participants found HapticCollider and the standard VR controller in terms of realism. The questions were open answered by participants and are shown below:

- Q7. What about the controller made the virtual reality feel more realistic?
- Q8. What about the controller made the virtual reality feel less realistic?

Both questionnaires were answered after each participant performs a condition. The participants answered the questions from an online form service, and the questions were therefore stored online.

4.3 Apparatus

Our apparatus consisted out of one commercial setup for VR, including a standard VR controller from HTC Vive as well as HapticCollider – our customized controller. Regarding the VR setup, we used an HTC Vive VR bundle, which according to existing literature is considered the standard VR solution for scientific research due to its accuracy [4, 24]. For the VR setup, we used three tracking cameras (unit of the HTC SteamVR Base Station 2.0), one VR headset (unit of the HTC Vive Pro), two standard HTC Vive handheld controller 2.0, and as PC to run the VR application an Intel(R) Xeon(R) CPU 3.60GHz, 16 GB RAM memory with an NVIDIA GeForce RTX 2080 Ti.

The VR environment is a garage containing a column in the middle and where the target, either a nail or a glass, is located at the eye's height of each participant. Above the target, we display a counter that states the number of the executed tasks. During each task, the target has to be hit with the virtual hammer five times. The virtual hammer is a representation of either HapticCollider or the standard VR controller, depending on the condition.

When the virtual hammer hits the nail, it moves a little inside the column, just like it does in the real world. Simultaneously, a set of sparks appears to visually complement the collision. In the glass hammering scenario, for every hit the glass breaks and leaves a hole where the virtual hammer hits it, see Figure 1 b) and c).

4.4 Task & Procedure

In our study, we had 4 conditions as follows: HapticCollider hitting a nail, HapticCollider hitting a glass, the standard VR controller hitting a nail and the standard VR controller hitting a glass. In total 24 participants (7 female, 17 male) were recruited from our university campus via e-mail lists. Each participant performed the study by passing through the 4 conditions using a counter-balanced order. It is worth noting that all participants were right-handed and aged between 20 and 32 years, with a mean of 26.58 years (SD = 3.91).

To start the study, the participants stand in front of a VR column while holding either the HapticCollider or the standard VR controller. They were asked to use the virtual hammer and hit 5 times a nail to move it into the wall or to smash the glass. HapticCollider generates force feedback, whereas the standard VR controller provides vibrotactile feedback when hitting the nail or glass. The virtual targets to be hit were located at the participant's eye level. After each condition, the participants were asked to answer the questionnaires described previously.

5 RESULTS

We first examined the quantitative questionnaire data using inferential statistics to identify whether using the HapticCollider during a VR experience is more realistic than using a conventional VR controller. We then analyzed the qualitative interview data applying Grounded Theory using axial and selective coding to better understand why one device might be more or less realistic than the other one and how the HapticCollider controller could be improved.

5.1 Quantitative Data

To assess the difference in *realism* between using the HapticCollider as a VR controller and using the standard VR controller, we conducted Wilcoxon Signed-Rank tests as part of our analysis. The choice of this test was motivated by the non-parametric nature of the data and the within-subjects design of our study. The results of the Wilcoxon Signed-Rank test indicated that the HapticCollider VR controller was perceived as significantly more realistic than the standard VR controller ($p < 0.001$) across all six subscales. The detailed results can be found in Table 1 and the corresponding boxplot is presented in Figure 4.

Subscales	Haptic-Collider medians	Std. VR controller medians	*Z-value*	*p-value*
Comparable experience	5.0	4.5	-3.828	< **.001**
Perceived realism	5.0	3.0	-4.582	< **.001**
Plausible Interaction	5.0	4.0	-3.740	< **.001**
Influence	6.0	5.0	-3.586	< **.001**
Real objects	5.0	4.0	-3.976	< **.001**
Resistance	5.0	2.0	-5.470	< **.001**

Table 1. Significance test results for realism between devices.

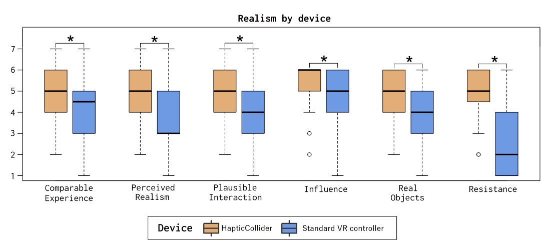

Fig. 4. Realism rating subscales: Comparable Experience, Perceived Realism, and Plausible Interaction measured with a 7-point Likert Scale (1 = not at all, 7 = completely). Realism rating subscales: Influence, Real Objects, and Resistance measured with a 6-point Likert Scale (1 = strongly disagree, 6 = strongly agree).

Wilcoxon Signed-Rank tests were also conducted to determine whether the participants perceived the two experimental differently in terms of *realism*. We found that five out of six subscales did not show a difference in *realism* between hammering a nail and smashing glass. Only the Influence subscale was perceived significantly less realistic when smashing glass compared to hammering a nail (Z=-2.127, p=0.033) as shown in Table 2 and in Figure 5.

	Nail medians	Glass medians	*Z-value*	*p-value*
Comparable Experience	5.0	5.0	-1.724	0.084
Perceived Realism	4.0	4.5	-1.493	0.135
Plausible Interaction	5.0	5.0	-1.688	0.091
Influence	5.0	6.0	-2.127	**0.033**
Real Objects	4.0	4.0	-0.720	0.471
Resistance	4.0	4.0	-0.701	0.482

Table 2. Realism rating per task.

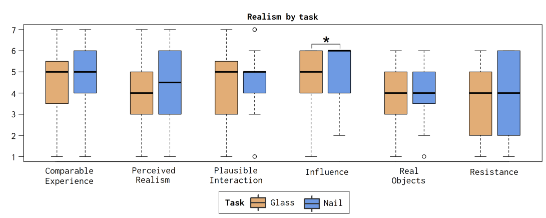

Fig. 5. Realism rating subscales: Comparable Experience, Perceived Realism, and Plausible Interaction measured with a 7-point Likert Scale (1 = not at all, 7 = completely). Realism rating subscales: Influence, Real Objects, and Resistance measured with a 6-point Likert Scale (1 = strongly disagree, 6 = strongly agree).

5.2 Qualitative Data

Two authors analyzed 192 answers from participants and then classified them in predefined codes. This feedback explaining our quantitative results, in particular why HapticCollider was more and why the standard VR controller was less realistic. They further extracted data describing how the HapticCollider device could further be improved to define the requirements of a next phase in an iterative design procedure.

Coding for HapticCollider

Axial Coding	Nail	Glass	Selective Coding
General haptic feedback	2	3	Force feedback
Resistance, sense of collision, force feedback	13	12	
Grip shape	1	1	Tool's weight and form factor
Weight	6	13	
Action has an effect on scene	3	7	Multimodal feedback
Visual feedback	4	2	
Sound	1	1	

Table 3. Axial coding for the HapticCollider, its repetitions counted per task: nail and glass, and its selective coding.

Coding for HapticCollider improvement

Axial Coding	Nail	Glass	Selective Coding
Real haptic feedback, force adjustment to speed	9	4	Force feedback
Weight change to reset	2	0	Tool's weight
Sound more realistic	4	3	Multimodal feedback
Timing, tracking offset	3	3	
More realistic vision	0	3	

Table 4. Axial coding for HapticCollider improvement, its repetitions by nail and glass, and its selective coding.

Coding for VR controller

Axial Coding	Nail	Glass	Selective Coding
Lack of haptic feedback	3	3	Force feedback
Resistance missing	14	12	
Weight or too light	13	10	Tool's weight and and form factor
Form factor	3	1	
Mismatch of action in in VR versus real	1	1	Multimodal feedback
Missing realistic sound	2	1	
Missing visuals	1	0	

Table 5. Axial coding for the standard VR controller, its repetitions by nail and glass, and its selective coding.

The qualitative data obtained from the participants in the semi-structured interviews after each of the four conditions was analyzed using Grounded Theory [35], in particular, axial and selective coding with the coding categories structured according to aspects that increased our limited the realism perception of the devices.

As our three coding rounds yield similar coding results, we document in the following paragraphs quotes that provide more details about the single codes from three different perspectives: explaining why the HapticCollider device was perceived realistic (see Table 3), how the HapticCollider device could be further improved (see Table 4), and why the VR controller lacks realism (see Table 5). These perspectives can serve as base to understand the reasons behind our quantitative results, as well as to critically look at challenges that should be addressed during the next HapticCollider prototyping iteration.

5.2.1 Code: Force feedback. Answers to the question: *"What about the controller made the virtual reality feel more realistic?"* regarding the use of HapticCollider explain why HapticCollider was perceived significantly more realistic than the standard VR controller. In total, 2 (nail) and 3 (glass) of 24 participants mentioned straight forward to have perceived the haptic feedback when they hit these objects in the virtual environment.

- *"The haptic feedback had the greatest effect" (P20)*
- *"The haptic feedback helped" (P1)*

In the same sense, 13 (nail) and 12 (glass) of 24 participants mentioned have perceived sensations such as resistance, sense of collision and force feedback during the impacts using HapticCollider.

- *"It hits like a natural hammer and the collision between hammer and block seems bit natural" (P5)*
- *"The resistance felt real" (P10)*

However, participants were expecting to recognize a difference in the haptic feedback between hitting a nail and breaking a glass. This insight is consistent with the HapticCollider capabilities and limitations.

- *"resistance was more realistic for the nail, different resistance expected" (P13)*

Similarly, participants reported that the force feedback generated by HapticCollider matches with hitting a solid object or even the force feedback was a little stronger than they excepted. For instance:

- *"I would say, the hit resistance was to high, it felt like I was hitting a wall or a really heavy metal object, to much for a small nail." (P9)*
- *"In my opinion, the resistance should be slightly less," ... ",to make it feel even more realistic." (P24)*

The question *"What happened to the controller that made VR feel less realistic?"* helped us to understand why the HTC Vive controller lacked realism compared with our HapticCollider device. Overall, 13 (nail) and 12 (glass) participants found that there was no resistance while hitting the virtual object:

- *"feedback was way too little." (P1)*
- *"The resistance after the hit was a little too light" (P12)*

5.2.2 Code: Tool's weight and grip form. The weight of the hammer is another factor that participants reported. 6 (nail) and 13 (glass) of 24 participants found the weight of HapticCollider as an enriching factor of the experience. For instance:

- *"The weight of the controller, gives a feel of a real hammer" (P14)*
- *"Weight closer to a real Hammer" (P22)*

Moreover, 1 (nail) and 1 (glass) participants found that the grip form match with a real hammer.

- *"the shape and weight of that." (P7)*

However, one participant reported that the weight distribution of the HapticCollider is different to a real hammer, this is because most of the HapticCollider mechanism is located on one side of the handle.

- *"Weight distribution of the controller does not correspond to that of a hammer." (P22)*

As critique regarding the standard VR controller, 15 (nail) and 11 (glass) participants did not associate the weight and form of the grip with a real hammer, as it is shown, e.g., in these quotes:

- *"The weight and form of the controller did not help to make me believe I had a hammer in my hands" (P19)*
- *"The controller didn't weigh as much as a real hammer" (P22)*

5.2.3 Code: Multimodal feedback. 3 (nail) and 7 (glass) comments stated that manipulating virtual objects by the action of HapticCollider through multimodal feedback increases realism, for instance:

- *"The combination from feeling a resistance and seeing the nail go deeper and deeper in the wall was quite realistic." (P9)*

In addition, 4 (nail) and 2 (glass) participants found that visual feedback, such as collision sparks and the visual representation of the hammer in VR, help to perceive a more realistic experience.

- *"The Controller moving and therefore giving me a reaction to my actions helped with the scene feeling more realistic." (P17)*

As an opportunity for improvement, 1 (nail) and 1 (glass) participants mentioned that including digital sound as feedback could even enrich the experience. In our study, only passive analog sound during the force feedback activation was provided when the hammer hit the target.

- *"a straight hitting glass sound would be handy" (P18)*

In the same way, one participant reported that the applied force to hit the nail did not match the displacement of it, in the virtual environment.

- *"Different impact strengths moved the nail the same distance. No noticeable difference on harder hits." (P1)*

The disadvantages of the standard VR controller in terms of realism were assessed by asking participants to provide feedback on the factors contributing to a reduced sense of realism in VR, see Q7, Q8. In answers, four participants (3 after the nail and after the 1 glass condition) expressed a desire for auditory cues, despite wearing headphones to reduce external noise.

- *"there weren't any sound of hitting" (P7)*
- *"no noise" (P21)*

6 DISCUSSION

In recent years, there has been an increasing amount of studies to investigate how to increase the realism within VR experiences through handheld controllers using haptic feedback. In this context, we designed HapticCollider, a handheld controller capable of generating ungrounded force feedback which significantly increases realism when hitting virtual objects in a VR hammering task compared to a standard VR controller.

Qualitative results provided three reasons why our HapticCollider controller increases realism: force feedback, tool weight and grip, and multimodal feedback, which are discussed below:

6.1 Force Feedback

The concept of force feedback was the most often mentioned reason for the significant realism increase of the HapticCollider device compared with the standard VR controller. In particular, "resistance", "the sensation of collision", and "force feedback" were mentioned.

It is commonly known that, if adding feedback of another modality, which here was haptic feedback in terms of force, it has to be consistent with the information of all other feedback modalities [42], which is in our case the 3D visual output. The control-display ratio, the technique described earlier, in 3.2, that stopped the visual motion even though the physical motion was ongoing, obviously supported the realism of the scene. Otherwise, realism would have been decreased.

While it has been shown that it is crucial that feedback given through different modalities has to be provided in both, spatial and temporal synchrony [43], the content of the information given in spatial and temporal synchrony by haptic and by visual feedback has still to provide the same experience and expectation so that the overall situation feels real.

Through the HapticCollider device, we have shown that a force feedback provided at the moment a virtual object is hit can be perceived as collision. With that, we introduce a novel haptic feedback sub-modality and show that it enriches user experience in VR.

6.2 Weight and Grip

We have built the HapticCollider device through deconstructing a real hammer. We used the original wooden grip and the steel hammerhead as weight that hits against the grip when a virtual collision appears. Hence, the grip felt natural, as the wooden material provided the exact same haptic experience in VR as known from analog hammers.

Even though a few more elements were added, such as the servo motor and the Arduino, the weight of HapticCollider (1044 grams) was perceived to be similar to an original hammer (about 900 grams) as confirmed by our participants.

In comparison, the standard VR controller is made from plastics and more lightweight. That is perceived to differ from a real hammer, even through in VR a hammer is visualized as the virtual representation of the controller.

For practical reasons, having a controller with a natural form factor for each possible VR application is surely impossible. Hence, we acknowledge the concept of generic controllers those form factor can always only be a compromise of a tool representation. However, for some purposes, such as professional training scenarios, e.g., handcraft education or surgery practice, special designed controllers with realistic form factors might be worth using.

6.3 Multimodal Feedback

As we discussed previously, the force feedback yielded by HapticCollider matches the impact of it with a virtual object. This haptic feedback is complemented visually by the haptic illusion which stop the virtual hammer in the position where it impacts the nail or the glass, as happens in a real hammering experience.

Previous work has been shown that a virtual environment is perceived richer if more modalities, in our case vision, haptic and the analog audio of the collision, are provided [33]. Moreover, and as discussed earlier, the information of each modality has to feed into a consistent whole [10]. We are glad that our implementation fulfilled that requirement and hence, it can be shown that our concept of force feedback truly represents a haptic collision feedback experience.

In comparison, the standard VR controller does not offer such haptic experience and participants really missed that even though vision is known to be in VR the dominant modality in motor actions [37].

In general, our visual scene seemed to be well modeled and convincing. Only the animation when the glass was smashed was perceived less realistic than the nail disappearing into the wall when being hit. This is shown by the significant differences between the task realism ratings and could be improved by a more advanced glass animation.

6.4 Integration of factors & challenges

HapticCollider's ability to integrate all four factors previously described in this section: force feedback, multimodal feedback, weight, and grip, enables to generate a realistic VR tool usage experience. The realistic force feedback while holding a controller that feels like a hammer and seeing a convincing scene in VR provides a rich, realistic, and consequently immersive VR experience. As we experienced in our iterative development process and through qualitative feedback that some aspects might not be obvious but are crucial to integrating all mentioned factors into a coherent and consistent experience, we will here discuss challenges in force feedback integration.

Collision Prediction Algorithm: Although the collision prediction algorithm was able to compensate for the perceived latency in force feedback for most of the participants, some of them reported a small latency. To resolve this issue, in the next HapticCollider iteration, an adaptive algorithm could calculate the prediction in consideration of the way a user swings the controller and its speed.

Control-Display Ratio: During the visual illusion implemented in the hammering interaction, there is a latency in the relocation of the virtual hammer after the hammer returns to the point of impact. This was again because the algorithm was designed for a range in hammer speed. Similarly, as in the previous issue, based on the user hammering speed, an adaptive algorithm could predict the return speed of the controller, and thus, calculate the correct point and moment to show the virtual hammer avoiding visual jumps.

Force feedback: HapticCollider was implemented to generate the same force feedback for each impact, regardless of the force with which the virtual object is struck or the material type of the impacted object. However, this aspect would make to vary the force in a hammering experience in the world real. This fact was reported by the participants, they expected to recognize a difference in force feedback between hitting a nail and breaking glass, but both were perceived to the same degree.

Summary & future work The described and discussed aspects are consistent with the capabilities and limitations of HapticCollider and suggest that the force feedback generated by HapticCollider could be improved by mapping the feedback from hitting different materials, and also mapping the spectrum of forces, from soft to hard, rather than just generating the same force for each impact, as currently established.

In addition, we really believe that it is possible to improve the collision prediction algorithm and the control-display ratio for a wide range of hammer speeds, thus, avoiding latencies as they are unrealistic haptic feedback, as it is discussed by Muender et al. [22].

7 SCALABILITY OF HAPTICCOLLIDER FOR OTHER APPLICATIONS

The haptic properties of HapticCollider can be adjusted and customized in three ways to use it in various applications. The first adjustment, highlighted in Figure 6 and referred to in the following text with (1), involves simulating different hitting materials, to generate different levels of force feedback and vibration of the grip. This can be done using a revolver cylinder which stores in each chamber materials like steel, wood, rubber, or concrete and allows changing the point of impact between the hitting weight and the handle. By simulating different materials, the user can experience a wider range of haptic sensations in different scenarios. Another adjustment could involve interchangeable weights, to which we refer to in Figure 6 with (2). HapticCollider can support a range of metal weights that can be easily changed to increase or decrease the impact force generated. The heavier the weight, the greater the impact force and vice versa. Finally, HapticCollider could come with a set of interchangeable grips that can be adapted to resemble a range of tools, including baseball bats, drumsticks, fishing rods, and hammers. This level of customization, shown in Figure 6 under (3), combined with the previous adjustment, enables users to perceive HapticCollider as a unique tool for each virtual experience. Thus, various applications can be supported, of which we describe – beside hammering – three more alternatives in the following paragraphs.

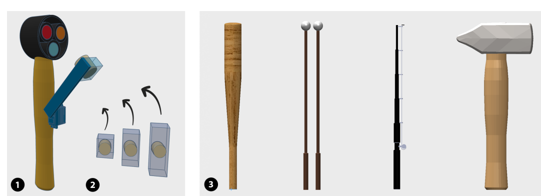

Fig. 6. (1) Concept idea of HapticCollider with interchangeable materials using a revolver cylinder (2) Interchangeable metal weights for HapticCollider (3) Set of interchangeable grips for HapticCollider, grips from left to right: baseball bat, percussion instrument, rod, and hammer.

Baseball bat: White et al. [41] identified that providing force feedback for heavy tools, like a baseball bat, can be challenging because the effectiveness of vibrotactile feedback decreases with increased weight. HapticCollider can address this challenge with the combination of three adjusments. It can simulate the impact between a baseball bat and ball by using the wood chamber (1). HapticCollider can be transformed into a baseball bat utilizing the interchangeable bat grip (2). The original weight can make HapticCollider feel like a baseball bat when gripped (3).

Playing percussion instrument: In order to simulate a drumming session, HapticCollider can be adjusted by changing the interchangeable revolver to a rubber material (1), which mimics the tip of a real drumstick. To reduce the overall weight of the device (2), a lighter weight should be added. Although this adjustment may generate less force feedback, it can still provide the desired haptic feedback during virtual drumming activities. Furthermore, an interchangeable grip that resembles a drumstick can be attached to the HapticCollider (3). The combination of grip customization, weight, force feedback, and using two devices, one for each hand, enables the user to perceive the experience as drumming.

Fishing rod: To adjust HapticCollider to simulate a fishing rod, the controller must be rotated 180 degrees. This allows users to feel a push force feedback generated by a virtual fish, which is caught by the fishhook and trying to get away. An interchangeable grip that resembles a fishing rod must be attached to the controller (3). This grip must allow grasping the controller with two hands as a real fishing rod. To mimic the weight and the force feedback of a fishing rod, a heavier impact weight could be installed (2). To simulate this scenario, HapticCollider can use the rubber chamber (1).

Hammering: To enhance the realism of hammering rigid objects in VR games, HapticCollider can provide collision force feedback for various materials (1). For instance, hitting a brick can be simulated using the concrete chamber of the revolver cylinder. Similarly, the process of hammering a nail into wood can be simulated by using the steel chamber of the revolver cylinder while hitting the nail and then switching to the wood chamber to provide haptic feedback when the nail is inserted. This can improve the user experience of hammering in VR games such as Demolish & Build [29] and cyubeVR [36], which use hammers and pickaxes respectively for destruction and digging. To simulate the scenarios of hammering, HapticCollider can use the original weight (2) and the original hammer grip (3).

8 CONCLUSION

Aiming to enrich VR experiences through novel haptic feedback techniques, we introduced a VR controller that provides users with force feedback on arm motion collisions. Such collision could, for example, be the object hit when hammering, the instrument hit when playing drums or a hit from the counterpart during boxing.

We introduced HapticCollider, a VR controller that provides ungrounded force feedback through a hit on the held controller in the opposite direction than the arm motion. The collision is further supported through display ratio, a visual replacement of the hammer and the hand so that both stop in the moment of the collision.

A user study showed that HapticCollider significantly increases realism compared with a standard VR controller and indicated that the provided force feedback, a naturalistic controller weight and form factor (using a wooden grip from a real hammer) supported realism in the multimodal experience in VR.

We conclude by highlighting aspects crucial to consider when implementing ungrounded force feedback and propose promising aspects to address in future research, as we believe that there is much more about force feedback that is worth to be investigated. This is demonstrated through multiple applications, which we propose to enrich with force feedback using the HapticCollider principle.

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REFERENCES

[1] Jonas Auda, Nils Verheyen, Sven Mayer, and Stefan Schneegass. 2021. Flyables: Haptic Input Devices for Virtual Realityusing Quadcopters. In *Proceedings of the 27th ACM Symposium on Virtual Reality Software and Technology* (Osaka, Japan) *(VRST '21)*. Association for Computing Machinery, New York, NY, USA, Article 40, 11 pages. https://doi.org/10.1145/3489849.3489855

[2] Mahdi Azmandian, Mark Hancock, Hrvoje Benko, Eyal Ofek, and Andrew D. Wilson. 2016. Haptic Retargeting: Dynamic Repurposing of Passive Haptics for Enhanced Virtual Reality Experiences. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (San Jose, California, USA) *(CHI '16)*. Association for Computing Machinery, New York, NY, USA, 1968–1979. https://doi.org/10.1145/2858036.2858226

[3] Rosa María Baños, Cristina Botella, Azucena Garcia-Palacios, Helena Villa, Concepción Perpiñá, and Mariano Alcaniz. 2000. Presence and reality judgment in virtual environments: a unitary construct? *CyberPsychology & Behavior* 3, 3 (2000), 327–335.

[4] Miguel Borges, Andrew Symington, Brian Coltin, Trey Smith, and Rodrigo Ventura. 2018. HTC Vive: Analysis and Accuracy Improvement. In *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, Madrid, Japan, 2610–2615. https://doi.org/10.1109/IROS.2018.8593707

[5] Inrak Choi, Eyal Ofek, Hrvoje Benko, Mike Sinclair, and Christian Holz. 2018. *CLAW: A Multifunctional Handheld Haptic Controller for Grasping, Touching, and Triggering in Virtual Reality*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3173574.3174228

[6] Richard E. Fan, Martin O. Culjat, Chih-Hung King, Miguel L. Franco, Richard Boryk, James W. Bisley, Erik Dutson, and Warren S. Grundfest. 2008. A Haptic Feedback System for Lower-Limb Prostheses. *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 16, 3 (2008), 270–277. https://doi.org/10.1109/TNSRE.2008.920075

[7] Cathy Fang, Yang Zhang, Matthew Dworman, and Chris Harrison. 2020. *Wireality: Enabling Complex Tangible Geometries in Virtual Reality with Worn Multi-String Haptics*. Association for Computing Machinery, New York, NY, USA, 1–10. https://doi.org/10.1145/3313831.3376470

[8] Ronan Gaugne, Valérie Gouranton, Georges Dumont, Alain Chauffaut, and Bruno Arnaldi. 2014. Immersia, an open immersive infrastructure: doing archaeology in virtual reality. *Archeologia e Calcolatori* 5, 1 (2014), 1–10. https://hal.science/hal-01003383

[9] Takashi Goto, Swagata Das, Katrin Wolf, Pedro Lopes, Yuichi Kurita, and Kai Kunze. 2020. Accelerating Skill Acquisition of Two-Handed Drumming Using Pneumatic Artificial Muscles. In *Proceedings of the Augmented Humans International Conference* (Kaiserslautern, Germany) *(AHs '20)*. Association for Computing Machinery, New York, NY, USA, Article 12, 9 pages. https://doi.org/10.1145/3384657.3384780

[10] RM Held and NI Durlach. 1992. Telepresence. Presence: Teleoperatorsand Virtual Environments, 1 (1), 109-112. Hendrix, C, & Barfield, W.(1996). Presence within virtual environments as a function ofvisual display parameters. *Presence: Teleoperators and Virtual Environments* 5, 2 (1992), 5–39.

[11] Seongkook Heo, Christina Chung, Geehyuk Lee, and Daniel Wigdor. 2018. Thor's Hammer: An Ungrounded Force Feedback Device Utilizing Propeller-Induced Propulsive Force. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–11. https://doi.org/10.1145/3173574.3174099

[12] Caroline Jay, Mashhuda Glencross, and Roger Hubbold. 2007. Modeling the Effects of Delayed Haptic and Visual Feedback in a Collaborative Virtual Environment. *ACM Trans. Comput.-Hum. Interact.* 14, 2 (aug 2007), 8–es. https://doi.org/10.1145/1275511.1275514

[13] Seungwoo Je, Myung Jin Kim, Woojin Lee, Byungjoo Lee, Xing-Dong Yang, Pedro Lopes, and Andrea Bianchi. 2019. Aero-Plane: A Handheld Force-Feedback Device That Renders Weight Motion Illusion on a Virtual 2D Plane. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology* (New Orleans, LA, USA) *(UIST '19)*. Association for Computing Machinery, New York, NY, USA, 763–775. https://doi.org/10.1145/3332165.3347926

[14] Max Kinateder, Enrico Ronchi, Daniel Nilsson, Margrethe Kobes, Mathias Müller, Paul Pauli, and Andreas Mühlberger. 2014. Virtual reality for fire evacuation research. In *2014 Federated Conference on Computer Science and Information Systems*. IEEE, Warsaw, Poland, 313–321. https://doi.org/10.15439/2014F94

[15] Chih-Hung King, Martin O. Culjat, Miguel L. Franco, Catherine E. Lewis, Erik P. Dutson, Warren S. Grundfest, and James W. Bisley. 2009. Tactile Feedback Induces Reduced Grasping Force in Robot-Assisted Surgery. *IEEE Transactions on Haptics* 2, 2 (2009), 103–110. https://doi.org/10.1109/TOH.2009.4

[16] Effie Lai-Chong Law, Virpi Roto, Marc Hassenzahl, Arnold P.O.S. Vermeeren, and Joke Kort. 2009. Understanding, Scoping and Defining User Experience: A Survey Approach. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Boston, MA, USA) *(CHI '09)*. Association for Computing Machinery, New York, NY, USA, 719–728. https://doi.org/10.1145/1518701.1518813

[17] Susan J Lederman and Roberta L Klatzky. 2009. Haptic perception: A tutorial. *Attention, Perception, & Psychophysics* 71, 7 (2009), 1439–1459.

[18] Nianlong Li, Han-Jong Kim, LuYao Shen, Feng Tian, Teng Han, Xing-Dong Yang, and Tek-Jin Nam. 2020. HapLinkage: Prototyping Haptic Proxies for Virtual Hand Tools Using Linkage Mechanism. In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology* (Virtual Event, USA) *(UIST '20)*. Association for Computing Machinery, New York, NY, USA, 1261–1274. https://doi.org/10.1145/3379337.3415812

[19] Pedro Lopes, Alexandra Ion, and Patrick Baudisch. 2015. Impacto: Simulating Physical Impact by Combining Tactile Stimulation with Electrical Muscle Stimulation. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology* (Charlotte, NC, USA) *(UIST '15)*. Association for Computing Machinery, New York, NY, USA, 11–19. https://doi.org/10.1145/2807442.2807443

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

[21] Dan Morris, Hong Tan, Federico Barbagli, Timothy Chang, and Kenneth Salisbury. 2007. Haptic Feedback Enhances Force Skill Learning. In *Second Joint EuroHaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (WHC'07)*. IEEE, Tsukuba, Japan, 21–26. https://doi.org/10.1109/WHC.2007.65

[22] Thomas Muender, Michael Bonfert, Anke Verena Reinschluessel, Rainer Malaka, and Tanja Döring. 2022. Haptic Fidelity Framework: Defining the Factors of Realistic Haptic Feedback for Virtual Reality. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 431, 17 pages. https://doi.org/10.1145/3491102.3501953

[23] Ander Ramos Murguialday, Vikram Aggarwal, Aniruddha Chatterjee, Yoonju Cho, Robert Rasmussen, Brandon O'Rourke, Soumyadipta Acharya, and Nitish V. Thakor. 2007. Brain-Computer Interface for a Prosthetic Hand Using Local Machine Control and Haptic Feedback. In *2007 IEEE 10th International Conference on Rehabilitation Robotics*. IEEE, Noordwijk, The Netherlands, 609–613. https://doi.org/10.1109/ICORR.2007.4428487

[24] Diederick C. Niehorster, Li Li, and Markus Lappe. 2017. The Accuracy and Precision of Position and Orientation Tracking in the HTC Vive Virtual Reality System for Scientific Research. *i-Perception* 8, 3 (2017), 2041669517708205. https://doi.org/10.1177/2041669517708205 arXiv:https://doi.org/10.1177/2041669517708205 PMID: 28567271.

[25] Allison M Okamura. 2009. Haptic feedback in robot-assisted minimally invasive surgery. *Current opinion in urology* 19, 1 (2009), 102.

[26] Karan Rangarajan, Heather Davis, and Philip H. Pucher. 2020. Systematic Review of Virtual Haptics in Surgical Simulation: A Valid Educational Tool? *Journal of Surgical Education* 77, 2 (2020), 337–347. https://doi.org/10.1016/j.jsurg.2019.09.006

[27] Michael Rietzler, Florian Geiselhart, Julian Frommel, and Enrico Rukzio. 2018. Conveying the Perception of Kinesthetic Feedback in Virtual Reality Using State-of-the-Art Hardware. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3173574.3174034

[28] Michael Rietzler, Gabriel Haas, Thomas Dreja, Florian Geiselhart, and Enrico Rukzio. 2019. Virtual Muscle Force: Communicating Kinesthetic Forces Through Pseudo-Haptic Feedback and Muscle Input. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology* (New Orleans, LA, USA) *(UIST '19)*. Association for Computing Machinery, New York, NY, USA, 913–922. https://doi.org/10.1145/3332165.3347871

[29] Demolish Games S.A. 2018. *Demolish & Build*. Game [Steam].

[30] Makoto Sato, Xiangning Liu, Jun Murayama, Katsuhito Akahane, and Masaharu Isshiki. 2008. *A Haptic Virtual Environment for Molecular Chemistry Education*. Springer-Verlag, Berlin, Heidelberg, 28–39.

[31] Mel Slater et al. 1999. Measuring presence: A response to the Witmer and Singer presence questionnaire. *Presence: teleoperators and virtual environments* 8, 5 (1999), 560–565.

[32] J. Solis, C.A. Avizzano, and M. Bergamasco. 2002. Teaching to write Japanese characters using a haptic interface. In *Proceedings 10th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. HAPTICS 2002*. IEEE, Orlando, FL, USA, 255–262. https://doi.org/10.1109/HAPTIC.2002.998966

[33] Jonathan Steuer. 1992. Defining virtual reality: Dimensions determining telepresence. *Journal of communication* 42, 4 (1992), 73–93.

[34] Patrick L. Strandholt, Oana A. Dogaru, Niels C. Nilsson, Rolf Nordahl, and Stefania Serafin. 2020. *Knock on Wood: Combining Redirected Touching and Physical Props for Tool-Based Interaction in Virtual Reality*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3313831.3376303

[35] Anselm Strauss and Juliet M Corbin. 1997. *Grounded theory in practice*. Sage, Thousand Oaks, CA, USA.

[36] Stonebrick Studios. 2018. *cyubeVR*. Game [SteamVR].

[37] Pascale Touzalin-Chretien, Solange Ehrler, and André Dufour. 2010. Dominance of vision over proprioception on motor programming: evidence from ERP. *Cerebral cortex* 20, 8 (2010), 2007–2016.

[38] Ching-Yi Tsai, I-Lun Tsai, Chao-Jung Lai, Derrek Chow, Lauren Wei, Lung-Pan Cheng, and Mike Y. Chen. 2022. AirRacket: Perceptual Design of Ungrounded, Directional Force Feedback to Improve Virtual Racket Sports Experiences. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 185, 15 pages. https://doi.org/10.1145/3491102.3502034

[39] Hsin-Ruey Tsai, Ching-Wen Hung, Tzu-Chun Wu, and Bing-Yu Chen. 2020. ElastOscillation: 3D Multilevel Force Feedback for Damped Oscillation on VR Controllers. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3313831.3376408

[40] Yu-Wei Wang, Yu-Hsin Lin, Pin-Sung Ku, Yōko Miyatake, Yi-Hsuan Mao, Po Yu Chen, Chun-Miao Tseng, and Mike Y. Chen. 2021. JetController: High-Speed Ungrounded 3-DoF Force Feedback Controllers Using Air Propulsion Jets. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 124, 12 pages. https://doi.org/10.1145/3411764.3445549

[41] Michael White, James Gain, Ulysse Vimont, and Daniel Lochner. 2019. The Case for Haptic Props: Shape, Weight and Vibro-Tactile Feedback. In *Proceedings of the 12th ACM SIGGRAPH Conference on Motion, Interaction and Games* (Newcastle upon Tyne, United Kingdom) *(MIG '19)*. Association for Computing Machinery, New York, NY, USA, Article 7, 10 pages. https://doi.org/10.1145/3359566.3360058

[42] Bob G Witmer and Michael J Singer. 1998. Measuring presence in virtual environments: A presence questionnaire. *Presence* 7, 3 (1998), 225–240.

[43] Katrin Wolf, Markus Funk, Rami Khalil, and Pascal Knierim. 2017. Using Virtual Reality for Prototyping Interactive Architecture. In *Proceedings of the 16th International Conference on Mobile and Ubiquitous Multimedia* (Stuttgart, Germany) *(MUM '17)*. Association for Computing Machinery, New York, NY, USA, 457–464. https://doi.org/10.1145/3152832.3156625

[44] Youchan Yim and Fumihide Tanaka. 2021. Development of an Inflatable Haptic Device for Pain Reduction by Social Touch. In *Companion of the 2021 ACM/IEEE International Conference on Human-Robot Interaction* (Boulder, CO, USA) *(HRI '21 Companion)*. Association for Computing Machinery, New York, NY, USA, 86–88. https://doi.org/10.1145/3434074.3447134

[45] André Zenner and Antonio Krüger. 2019. Drag:On: A Virtual Reality Controller Providing Haptic Feedback Based on Drag and Weight Shift. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3290605.3300441

[46] 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. https://doi.org/10.1109/TVCG.2017.2656978