Novel Haptic Output for Spatial Input Devices and Controllers – HapticIO

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Abstract

This article presents HapticIO, a research project aimed at advancing haptic feedback technologies for spatial input devices and controllers in Extended Reality. We present four prototypes: HapticCollider, providing ungrounded force feedback for rigid collisions in virtual tool use; MorphGrip, offering shape-changing haptic guidance for precise manual tasks; PumpVR, rendering object and avatar weight using liquid mass transfer; and MobileGravity, enabling weight simulation in mobile scenarios. Furthermore, we derive a predictive model for optimizing weight rendering through a study assessing the effects of absolute mass and weight distribution. Additionally, each system is evaluated through empirical user studies, revealing significant improvements in realism. We discuss integrating these technologies into unified devices while addressing associated challenges.

1. Introduction

The current input for spatial interaction, such as in Augmented, Mixed, Extended and Virtual Reality (AR, MR, XR, VR), is mainly limited to camera-based systems and controllers for gesture-, button- and touch-based input. More complex manual actions, such as those required to inspect elements (e. g., touching a pump and detecting vibration and heat) or modeling 3D objects, are not yet possible due to the limited haptic input options. Haptic feedback in a more natural form is missing to make physical interactions with objects intuitive even over a distance.

Previous solutions can be improved in terms of the user experience as they only enable very simplified and therefore imprecise interaction.

As vibration cannot realistically simulate the entire range of haptic sensations we can perceive, developing controllers that provide haptic feedback beyond vibrotactile stimuli is therefore the vision of the project HapticIO (10/2021–08/2024). HapticIO is a joint project with the following partners: Berlin University of Applied Sciences and Technology (BHT), University of Regensburg, Konstruktiv GmbH, Intuity Media Lab GmbH, and Technical University Ingolstadt of Applied Sciences (THI).

The objective is to create haptic controllers that can be perceived as an analog user interface, thereby enabling users to utilize digital tools in a manner consistent with their traditional predecessors. Consequently, users who know how to use a drill should also be able to drill with a haptic controller through intuition and knowledge transfer. They should be able to do this just as well as with the traditional tool because the virtual tool feels and behaves exactly like its reference tool. The acquisition of skills is therefore transferred from the knowledge of how we handle traditional tools to their virtual and intelligent equivalents. The integration of sensors, actuators, and networking technologies also makes it possible to use virtual and intelligent tools in joint projects and to, for example, enable the transfer of knowledge between experts and learners.

Through such technological innovation, we can better develop technology to control digital reality, intelligent objects, and intelligent spaces around us. Haptic feedback devices were therefore developed in this project, for example, to enable

– the use of tools for collaborative work or training in virtual workshops,
– the use of multimodal AR, XR, and VR control elements for intelligent environments and
– interaction with intelligent tools in a mixed reality environment.

To explore how such systems should be developed, we designed and implemented artifacts and demonstrators that were evaluated in user studies, and which are presented in the following paragraphs. These include HapticCollider, a VR controller providing ungrounded force feedback for simulating collision forces; MorphGrip, a shape-changing device delivering haptic guidance for manual tasks; PumpVR, which adjusts the weight of VR controllers to match the properties of virtual objects through liquid mass transfer; and MobileGravity, a mobile proxy that simulates weight changes while ensuring user mobility. Finally, a study on weight perception explores how absolute mass and weight distribution impact realism, leading to predictive models for optimizing weight rendering. We conclude with a discussion on the potential for combining these technologies and the challenges involved.

2. HapticCollider

Researchers have been exploring VR controllers that offer more advanced haptic feedback beyond basic vibration, aiming to enhance realism in virtual tool use. However, providing realistic force and weight feedback, especially for heavy tools, remains a challenge. HapticCollider addresses this gap by simulating collision force feedback when using weighted tools, such as a hammer, without requiring external apparatus. HapticCollider aims to improve immersion in VR applications like hammering, baseball, or fishing, while offering a more realistic experience than standard controllers. This section is based on our corresponding publication at the Mensch und Computer conference (Olaya-Figueroa et al., 2023).

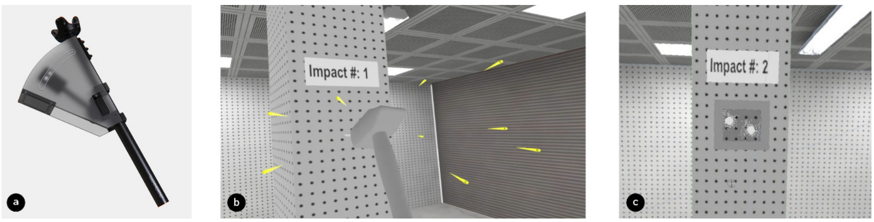

Figure 1: a) 3D model of HapticCollider created in the design phase and before assembly, b) HapticCollider in the virtual environment while hitting a nail and c) after breaking a glass
Source: Own representation based on Olaya-Figueroa et al., 2023: 116

2.1 Enhancing Force Feedback for Heavy Tools in VR

In VR, immersion refers to the degree to which the user feels present within a virtual environment (Slater et al., 1999: 1–13). Consequently, haptic feedback is essential for allowing users to perceive physical responses from the virtual world they experience. To achieve realistic haptic feedback, the concept of haptic fidelity outlines three key components that are relevant to our objective of designing a novel VR controller with force feedback: Sensing, Hardware, and Software (Muender et al., 2022: 1–17). Sensing refers to the ability to generate natural haptic sensations, while Hardware encompasses the elements responsible for generating these stimuli and the necessity of minimizing any potential delays caused by mechanical parts. Software refers to algorithms that regulate haptic sensations. For example, prediction algorithms can anticipate events and trigger haptic feedback ahead of time, reducing latency and ensuring that the haptic feedback remains synchronized with the visual cues. HapticCollider integrates these three components to create a realistic experience.

Despite the advancements in VR haptics, there remains a gap in delivering force feedback for heavy tools, such as a hammer or baseball bat, when striking rigid objects in VR. Addressing this gap, *HapticCollider* integrates these three components—Sensing, Hardware, and Software—to provide a realistic and immersive experience.

2.2 Prototype and Application

HapticCollider, a VR controller designed for realistic haptic experiences, utilizes a kinetic mechanism to simulate the impact of hammering a nail, integrating an Arduino interface and a powerful servomotor. (a) To protect participants' fingers a coverwas printed in 3D. (b) Key components of HapticCollider include a weighted mass that strikes a wooden handle when a collision is detected in the virtual environment, see Figure 2.

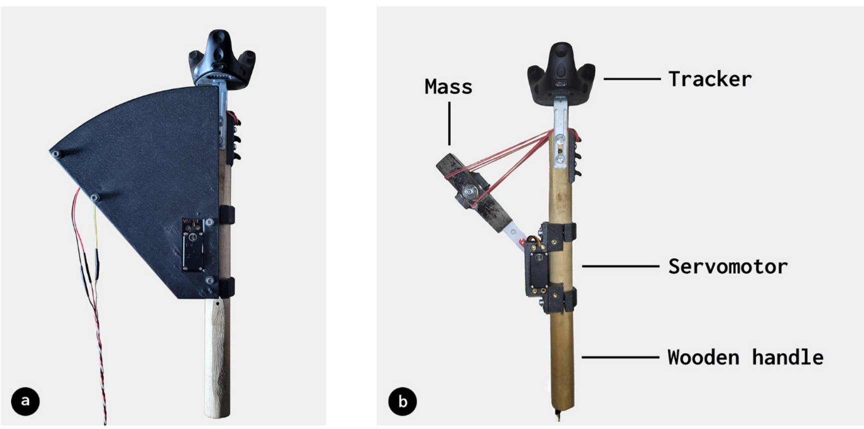

Figure 2: HapticCollider featuring (a) the cover to protect users and (b) its components
Source: Own representation based on Olaya-Figueroa et al., 2023: 119

Due to the mechanical elements of HapticCollider a slight latency is introduced to the force feedback, which may affect the realism of the experience. To address this, a collision prediction algorithm triggers force feedback just before a virtual collision, aligning haptic and visual cues in three steps (see Figure 3): (a) using an invisible ray to anticipate a collision by detecting if the direction of the hammer moves towards the target nail and that its speed is greater than a certain threshold; (b) once detected, the system initiates the collision effect, (c) stopping the hammer at the collision point in the virtual environment while the physical controller continues briefly. This control-display offset helps simulate the illusion of impact. HapticCollider is highly adaptable for various VR applications. It mimics the weight, grip, and impact of tools like baseball bats, drumsticks, and fishing rods, addressing challenges in vibrotactile feedback and enabling realistic interactions. It also provides collision feedback for materials like wood and concrete in hammering tasks, thus enhancing the realism of activities such as drumming, fishing, and construction in VR.

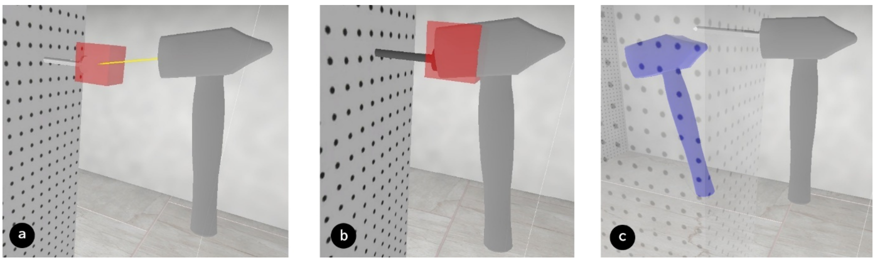

Figure 3: Steps of the collision prediction algorithm and the control-display ratio working while HapticCollider is hitting a nail.
Source: Own representation based on Olaya-Figueroa et al., 2023: 119

2.3 Results

In our study, 24 participants completed two tasks, once using HapticCollider and once using a standard VR controller. While HapticCollider provided force feedback, the standard VR controller delivered vibrotactile feedback. Participants stood in front of a VR column and used a virtual hammer to hit either a nail into a wall (Task 1) or smash glass (Task 2), with targets positioned at eye level. Upon each condition, participants completed questionnaires to obtain qualitative feedback and evaluate their perceived realism.

The user study demonstrated that HapticCollider significantly enhances the realism of virtual hammering tasks compared to a standard VR controller. Key factors included force feedback, controller weight, synchronized multimodal cues (visual, haptic) and the form factor since HapticCollider uses a hammer handle (Olaya-Figueroa et al., 2023: 120–125).

3. MorphGrip

Handheld devices, VR controllers, and tools often function as passive instruments, lacking responsiveness to user input and environmental events, which can limit their effectiveness in complex situations. While previous research has explored visual, auditory, and haptic feedback to guide users during manual motor tasks, shape-changing haptic feedback remains underexplored for tasks requiring precise translational and rotational movements. MorphGrip addresses this gap by providing tactile cues to the palm and fingers through dynamic grip adjustments. This design enables MorphGrip to guide users in performing manual motor tasks, such as translation and rotation, especially in industrial and therapeutic settings where auditory and visual cues may be overloaded or unavailable. This section is based on our corresponding publication at the International Conference on Mobile and Ubiquitous Multimedia (Olaya-Figueroa et al., 2024). MorphGrip is depicted in Figure 4. Figure 5 shows its inner mechanics.

Figure 4: A user is grasping MorphGrip.
Source: Own representation based on Olaya-Figueroa et al., 2024: 196

3.1 Haptic Guidance

Research in guidance systems has evolved across visual, auditory, and haptic modalities, each with distinct advantages and limitations. Haptic guidance, offering directional cues, provides a viable alternative, especially with devices like wearable bands (Tsai et al., 2021: 1–13) and vibrotactile (Weber, 2011: 349–354). However, existing research on haptic guidance for manual motor tasks has predominantly relied on external devices to provide directional cues. To date, no study has explored embedding guidance mechanisms directly into the grip of a device to assist users in such tasks. MorphGrip addresses this research gap by introducing a smart device with an integrated shape-changing grip that leverages the high sensitivity of the palm to deliver precise directional haptic cues. MorphGrip is specifically designed to provide self-guidance for manual motor tasks in eyes-free interactions. It is intended for scenarios where the visual channel is unavailable, impractical, or occupied by the task at hand.

3.2 Prototype and Application

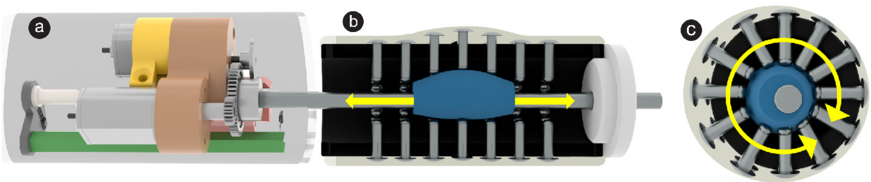

Figure 5: (a) The MorphGrip mechanism includes two motors: (b) one motor for generating the linear haptic cue and (c) the other for generating the circular haptic cue MorphGrip.
Source: Own representation based on Olaya-Figueroa et al., 2024: 200

MorphGrip is a shape-changing grip device designed to provide haptic guidance for manual motor tasks through two distinct haptic cues. It generates two types of feedback: a linear haptic cue (moving up/down) and a circular haptic cue (rotating clockwise/counterclockwise). The mechanism employs dual DC motors and an eccentric cam-follower system creating a movable wave crest pattern on the grip's surface by means of extendible pins. The design addresses three main challenges: implementing distinct haptic cues, embedding the mechanism within a cylindrical grip facilitating the integration into handheld devices, and maintaining mechanical simplicity for practical use in handheld devices and controllers. MorphGrip is engineered for diverse applications across multiple domains, including rehabilitation therapy, where it assists users in repetitive motor tasks to support physical recovery and training; smart tools in industrial settings, where it provides guidance for tools used in demanding environments; and specialized scenarios, such as underwater applications, where traditional visual and auditory cues are ineffective or unavailable. These applications highlight the versatility of MorphGrip as an innovative solution for scenarios requiring alternative guidance methods.

3.3 Results

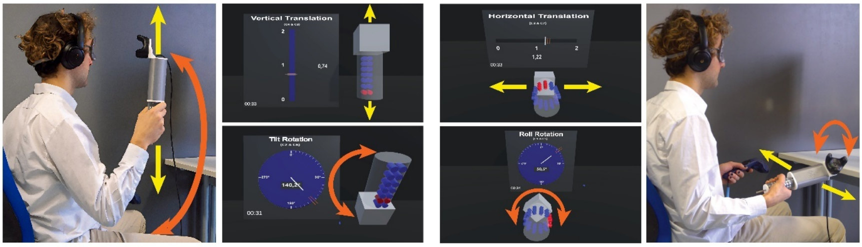

Figure 6: In the user study, participants performed 4 tasks being guided by MorphGrip: (Vertical, Horizontal) translations, and (Tilt, Roll) rotations MorphGrip.
Source: Own representation based on Olaya-Figueroa et al., 2024: 200

In our study, 24 participants performed four tasks, namely Vertical, Tilt, Roll, and Horizontal, guided by MorphGrip's linear and circular haptic cues. Each task involved reaching randomly assigned target points within specific ranges of height, tilt angle, rotation angle, or lateral position. The study compared the effectiveness of MorphGrip's haptic cues against verbal cues for guidance, evaluating performance based on success rate, task completion time, travel distance and overshooting. After completing each condition, participants filled out questionnaires to gather qualitative feedback and evaluate the task load based on their experiences. The procedure is illustrated in Figure 6.

The findings revealed that, although verbal cues outperformed haptic cues, participants found haptic cues helpful in completing tasks, with notably improved performance in the Horizontal and Vertical tasks. In contrast, the Roll and Tilt tasks demonstrated a higher mental demand, suggesting that these tasks may benefit from further refinement in haptic feedback design. Overall, MorphGrip shows strong potential for integration into handheld device grips, particularly in applications like rehabilitation therapy, industrial smart tools, and specialized environments such as underwater guidance, where visual or auditory cues may be limited or unavailable (Olaya-Figueroa et al., 2024: 196–209).

4. PumpVR

Perceiving the weight of virtual objects and avatars in virtual reality is important in order to understand their properties and to interact with them naturally. However, commercial VR controllers have a static, low weight, giving each virtual object and avatar the same sensation of weight. PumpVR uses a bidirectional pump and solenoid valves to change the weight of the VR controllers so that the perceived weight corresponds to the virtual properties (see Figure 7). This allows users to feel the weight of virtual objects or avatars, enhancing the realism and enjoyment of VR experiences. This section is based on our corresponding publication at the CHI Conference on Human Factors in Computing Systems (Kalus et al., 2023b).

Figure 7: PumpVR at three different weight levels and exemplary virtual objects that these can represent
Source: Own representation based on Kalus et al., 2023b: 4

4.1 Weight Simulation in VR

When interacting with objects in the real world, humans naturally perceive their weight, which influences their understanding of the object's properties and affects how they handle or manipulate it. This is largely absent in VR, where users sense the weight of their input device, which is typically different from the weight of the object seen in the virtual environment. Providing realistic weight sensations is therefore a key challenge for the progress of VR. In addition to rendering the weight of virtual objects, simulating the body weight of avatars in VR has been largely unexplored, yet it is crucial for enhancing the feeling of embodiment and thus the sense of being present in the virtual world.

Although previous research has attempted to address this gap by developing controllers capable of simulating weight, these systems suffer from several limitations, including single-handedness, a slow response time, or only being able to simulate small weight changes, as highlighted by Lim et al. (2021: 163270–163273) in their review on weight simulation in VR. These constraints hinder the effectiveness and practicality of such systems in a wide range of VR applications

4.2 Prototype and Application

The system renders up to 500 g per hand, reaching this weight by transferring water at a rate of 150 g/s into a reservoir located within each controller.

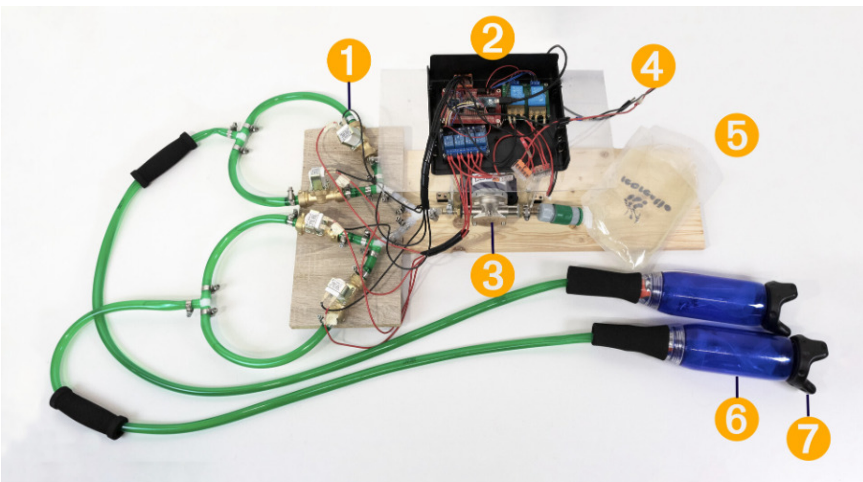

Figure 8: Components of PumpVR
Source: Own representation based on Kalus et al., 2023b: 5

Figure 8 shows PumpVR's components. The device employs a bi-directional pump (1) to allow reversing the water flow. Four solenoid valves (2) direct the flow of water, which is transferred between three water bags. Sealed foldable drinking bags were chosen, as they contract under negative pressure, avoiding the perception of liquid inertia. Two of them are placed inside the controllers' plastic housings (3). HTC Vive Trackers are screwed on top of these housings to enable positional and rotational tracking in the VR environment (4). A control unit (5), consisting of an ARDUINO MICRO, a bluetooth module and six relay modules, communicates with the game engine via Bluetooth and controls the flow of water depending on the in-app event.

We implemented two use cases to demonstrate PumpVR's capability of rendering the weight of virtual objects and avatars. The first application involves the user interacting with game items of different weights, such as a hammer, a torch, a shield, or bare hands. The game requires the users to switch between these items and use them to combat approaching enemies and block arrows. The purpose of the second application is to explore the use of PumpVR to render body weight. In the application, the volume of the user's virtual body and the weight of both controllers are increased simultaneously until the controllers reach their maximum weight.

4.3 Results

The system can produce distinct weight levels within the controllers. A technical evaluation showed that PumpVR could target five different weight levels efficiently by controlling the water-pumping duration, achieving consistent weight changes with an average deviation of less than 5 %.

We also conducted a user study in within-subject design, in which 24 participants completed both test applications using either PumpVR or a regular VR controller. We assessed realism, enjoyment and virtual embodiment using established instruments such as the Reality Judgment and Presence Questionnaire, the Intrinsic Motivation Inventory and the Virtual Embodiment Questionnaire. Utilizing PumpVR to render object weight yielded significantly higher realism and enjoyment scores compared to the use of regular VR controllers. Additionally, participants perceived their virtual body significantly more strongly as their own when PumpVR was used to simulate body weight. The detailed analysis can be found in the accompanying publication (Kalus et al., 2023b: 1–13).

5. MobileGravity

In this section, we present MobileGravity, a VR proxy that adapts its weight to the virtual object being held in VR. The system separates bulky and heavy components from the weight-adjusted object and thus addresses the conflict between mobility and performance. Furthermore, by enabling changes of up to 1 kg in 235 g/s, it outperforms previous approaches in terms of weight range and responsiveness. This section is based on our corresponding publication at the CHI Conference on

Human Factors in Computing Systems (Kalus et al., 2024b). Figure 9 illustrates the interaction with MobileGravity.

Figure 9: Interacting with MobileGravity
Source: Own representation based on Kalus et al., 2024b: 1; Kalus et al., 2024c: 1

5.1 Balancing Performance and Mobility of Weight Interfaces

To facilitate weight change, a liquid-based weight interface, such as PumpVR, requires a connection to an external reservoir, which restricts the user's mobility (Kalus et al., 2023a: 1–3). However, a broad range of VR experiences requires unhindered movement, including VR fitness training, sports simulations, or motion-based learning applications. Furthermore, the ability to walk around freely in VR increases the effectiveness of locomotion, enhances cognitive map building and reduces motion sickness, whereas grounded cable connections were found to disturb the experience (Langbehn et al., 2018: 1–9). Lim et al. (2021: 163253–163283) reviewed 65 research prototypes and highlighted the trade-off between mobility and performance as a key challenge for advancing weight interfaces. Hence, there is a clear need for mobile weight simulation that does not compromise on other desired objectives.

5.2 Prototype and Application

To address the aforementioned trade-off, we developed MobileGravity, which uses water to change the weight of a handheld VR proxy object, but decouples it from the water supply and heavy components once the weight is adjusted. This allows the user to walk and turn in any direction. MobileGravity consists of a mobile proxy object equipped with a water reservoir, an HTC Vive Tracker and two handles, and a base station with a pump and water tank. The two units connect through dripless quick disconnect couplings that automatically cut off the water flow when disconnected. A limit switch is used to continuously check if a connection is established. A recess in the top of the base station allows the user to insert the proxy object. To preserve immersion in VR, this insertion is facilitated via the user placing their handheld virtual object in a designated location in the virtual environment. This starts the weight adjustment. To separate the two units again after the weight adjustment, they are automatically unlocked by two solenoid actuators. The inner workings of MobileGravity are shown in Figure 10.

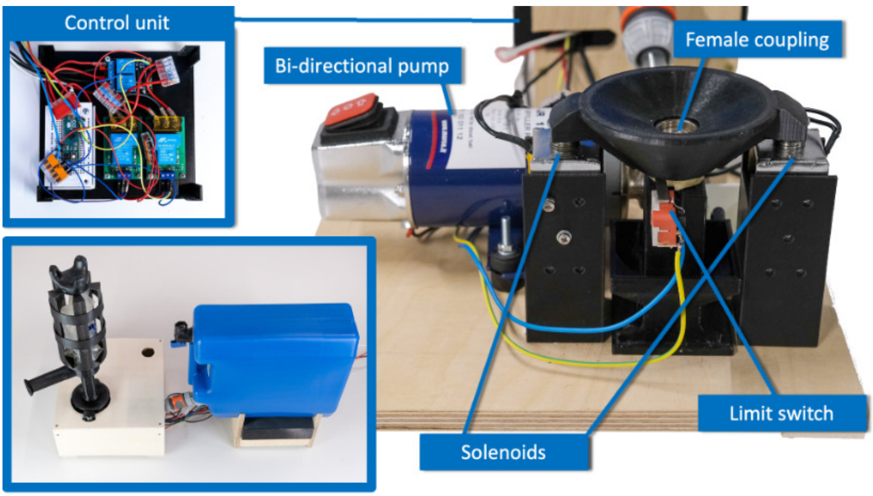

Figure 10: Inner workings of MobileGravity's base station and its connection to the handheld proxy (bottom left)
Source: Own representation based on Kalus et al., 2024b: 5

We created a virtual environment in Unity to test and demonstrate the concept. We chose a virtual workshop setting (see Figure 11), to feature objects with a broad range of weight in a coherent scenario. In the scene users can build a bird box using six virtual tools of different weight, i. e. a paint roller, a stapler, a hammer, a hacksaw, a blowtorch and a cordless drill.

Apart from the demonstrated application, we provide further use cases for MobileGravity (see Figure 12). Its adaptive weight feedback can be used to simulate different intensities of VR workouts. In our exemplary application, the user handles two MobileGravity proxy objects to hit objects of different colours that appear from the background, similar to popular fitness applications such as Beat Saber and FitXR. A further application consists of a co-operative, co-located game, in which users run through the virtual world and overcome enemies and obstacles. To do so, they are required to use specific virtual objects that require

Figure 11: Overview (left) and user's view (right) of the virtual workshop
Source: Own representation based on Kalus et al., 2024b: 6

different handling, which is perceptible through the weight feedback. Finally, MobileGravity can be used to perceive different avatar weights in room scale setups: In our third use case, the users wear two MobileGravity controllers on their bodies. The application adjusts the weight of the worn controllers to the expected body weight of the embodied avatar and decouples the user from the base station.

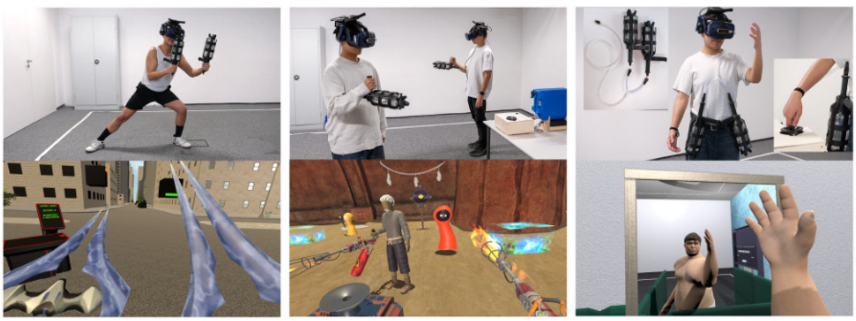

Figure 12: Further use cases for MobileGravity. VR workout (left), cooperative game (center), and avatar weight simulation (right)
Source: Own representation based on Kalus et al., 2024b: 10

5.3 Results

In a within-subject study, 30 participants were tasked with constructing a virtual bird box in the workshop environment using tools simulated with either MobileGravity or a standard VR controller. Measures included quantitative ratings of general and haptic realism, enjoyment, and qualitative feedback for deeper insights. Statistical analysis found that MobileGravity significantly enhanced general and haptic realism, as well as enjoyment. Furthermore, participants reported that using MobileGravity made the virtual tools feel more like their real-life counterparts and that they adapted their movements to the virtual tools due to the haptic feedback. The complete analysis and implementation can be found in the accompanying publication (Kalus et al., 2024b: 1–13).

6. Simulating Object Weight in VR: The Role of Absolute Mass and Weight Distributions

To understand the optimal weight to be provided when using weight interfaces such as PumpVR or MobileGravity, we conducted a study in which 30 participants assigned the most realistic weight to differently configured virtual objects. There were 54 object configurations, varying in level of visual mass, visual weight distribution and center of physical mass. We found that participants underestimated the weight of heavy objects and overweighted light objects. While the visual weight distribution did not affect the weight estimation, the physical center of mass did. We derive guidance for the design and utilization of weight interfaces and provide predictive models to determine the weight to render based on visual mass and visual weight distribution. This section is based on our corresponding publication at the ACM Symposium on Virtual Reality Software and Technology (Kalus et al., 2024a).

6.1 Weight Perception

An object's perceived heaviness depends not only on its absolute mass but also on its weight distribution (Amazeen & Turvey, 1996: 213–232). Additionally, our brain relies on visual cues and expectations to estimate an object's weight. For instance, in the size-weight illusion when humans lift two equally weighted but different-sized objects, they perceive the bigger object as lighter (Saccone et al., 2019: 1195–1212). In the golf ball illusion, golfers who are familiar with the weight of golf balls perceive their weight differently compared to non-golfers, who lack this knowledge (Ellis & Lederman, 1998: 193–201). Hence, prompting a weight interface, such as PumpVR or MobileGravity, to replicate a virtual object's absolute weight does not necessarily provide the most realistic haptic representation. Consequently, there is a clear gap in understanding how to determine the weight to render for a given virtual object.

6.2 User Study

We conducted a study to understand how to best use such weight interfaces to simulate realistic object weight. In the study, 30 participants (14 female, 16 male, aged 18–34) were asked to choose the best-fitting weight for virtual objects in 54 different experimental trials. These trials varied in three factors (see Figure 13): the visual mass of the object (three levels), the distribution of the object's weight (six levels), and the position of the physical mass on the object's grip (three levels). For each of the objects, participants saw 13 instances in VR that looked identical but were co-located with different physical weights in the real world, ranging from 100 g to 1300 g. They were instructed to pick up, wield and heft the different objects and were permitted to try any object until they felt that the haptic sensation most closely aligned with the virtual object.

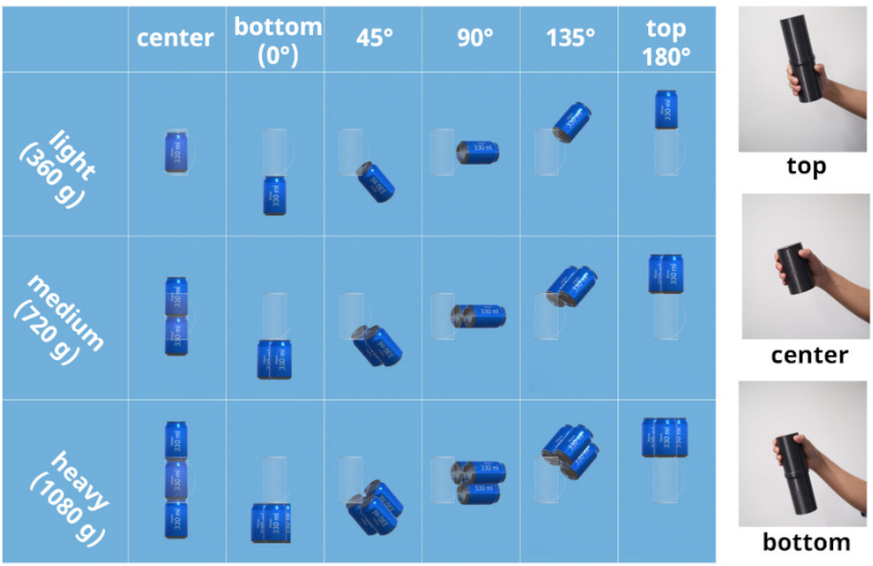

Figure 13: Experimental conditions
Source: Own representation based on Kalus et al., 2024a: 5

6.3 Results

Our Bayesian analysis revealed that participants underweighted heavier objects while overweighting lighter objects. This suggests that, for heavy objects, the absolute weight rendered by VR systems can be reduced without sacrificing perceived realism. This finding is beneficial in reducing several issues that come with simulating heavy weights, such as motor noise, latency, high power consumption and bulkiness. Additionally, the study found that the position of the physical mass significantly impacted weight perception. Objects with the physical mass placed at the top of the grip were perceived as lighter than those with the mass placed at the bottom. Interestingly, the visual center of mass did not influence weight perception. Hence, we fitted a linear model to predict the optimal weight to render for virtual objects based on the virtual object's visual mass and the position on which the weight interface can provide the physical mass position relative to the handle. The regression equation was: $w = 163.7\,g + 0.68 \times v + 1.75 \times p$, where w is the weight to render, v is the visual mass in grams and p is the physical mass's distance to the handle in cm. Developers can use this model to estimate the weight to be rendered by the weight interface, balancing realism and performance. Details on the methodology and results can also be found in the accompanying publication (Kalus et al., 2024a: 1–11).

7. Discussion and Conclusion

In sum, this research explored novel approaches to enhancing haptic feedback in VR, XR and AR environments. The development and evaluation of systems like HapticCollider, MorphGrip, PumpVR, and MobileGravity offer promising advancements in simulating realistic physical sensations by addressing challenges related to weight perception, force feedback, and shape-shifting.

During a workshop, we engaged in an open discussion about combining multiple prototypes into a single device. The consensus from this discussion was that, while it is technically possible to merge some of the presented systems, it often does not make much sense from the user's perspective. Table 1 presents potential use cases for each combination of the prototype technologies.

Several key factors contributed to our conclusion. First, the spatial constraints and the increase in weight associated with adding more technology to a single device would likely diminish the usability of the prototype. Users could struggle with holding or using devices that become heavier and bulkier as more functionalities are integrated. Second, there was concern about haptic sensations overlaying and distracting from one another, which could lead to overstimulation. When multiple haptic sensations and mechanisms are combined in a single prototype, they could potentially interfere with one another, resulting in a confusing or overwhelming user experience. Finally, while each system has valid use cases on its own, finding a single use case where multiple sensations are required often ap-

	HapticCollider	**PumpVR**	**MobileGravity**
MorphGrip	A VR scenario; controlling a crane with feedback on how hard something hit; golfing/baseball with rotation guidance	Tool training with weight and rotational information	Tool training with weight and rotational information
HapticCollider		VR fishing, impact when pulling up hard	Hammering, sword fighting

Table 1: Potential use cases for combined prototypes
Source: Own representation

peared to be a »solution seeks problem« scenario. In other words, while the individual technologies serve their individual purposes well, finding a direct user need where combining them is critical is rare. However, despite these challenges, creating a unified prototype that combines multiple haptic properties holds enormous potential for immersion in VR. Achieving this would require overcoming the current limitations, such as spatial constraints and overweight. As such, more research is necessary to explore how various haptic properties can be effectively integrated into a single device, without sacrificing usability, comfort, or user experience.

Funding information

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