MobileGravity: Mobile Simulation of a High Range of Weight in Virtual Reality

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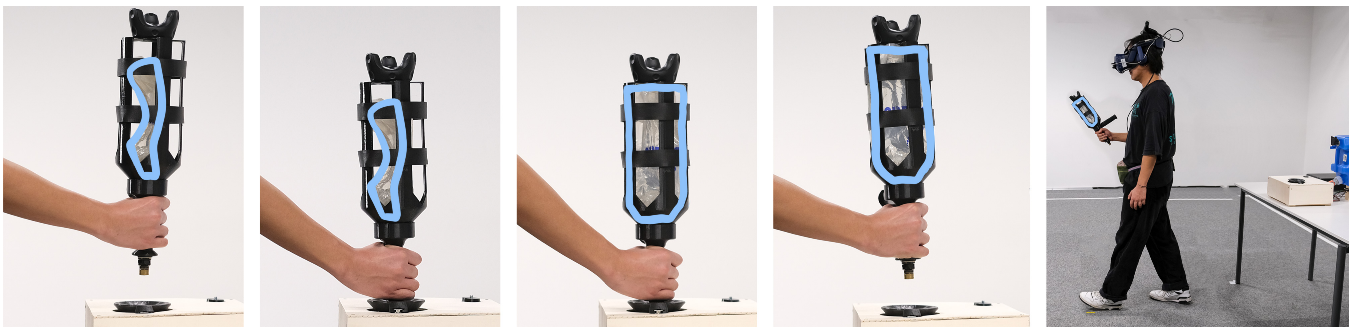

Figure 1: Procedure for adjusting the perceived weight through MobileGravity. The four images on the left show connecting MobileGravity's handheld proxy object with its base station, adjusting its weight, and disconnecting both components. The user can then move around freely (image on the right). The outline of the liquid reservoir inside the proxy object is highlighted.

ABSTRACT

Simulating accurate weight forces in Virtual Reality (VR) is an unsolved challenge. Therefore, providing real weight sensations by transferring liquid mass has emerged as a promising approach. However, key objectives conceptually interfere with each other. In particular, previous designs that support a high range of weight or high flow rate lack mobility. In this work, we present MobileGravity, a system, that decouples the weight-changing object from the liquid supply and the pump. It enables weight changes of up to 1 kg at a rate of 235 g/s and allows the user to walk around freely. Through a study with 30 participants, we show that the system enables users to perceive the weight of different virtual objects and enhances realism, as well as enjoyment.

CCS CONCEPTS

• **Human-centered computing** → **Haptic devices**; **Virtual reality**.

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KEYWORDS

virtual reality, haptics, weight perception, weight simulation

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1 INTRODUCTION

The perception of weight plays a crucial role in how we interact with objects [16], influencing factors such as our grip and lift force [54], our positional sense [2] and our aiming movements [9]. In VR, where users interact with objects that exist in a simulated environment, the sense of vision is stimulated separately from tactile and kinesthetic sensory modalities. When holding objects in VR, users sense the weight of their input device, which is typically different from the weight of the object depicted in the virtual world. This mismatch between the visual characteristics of a virtual object and the physical weight of the handheld controller has been shown to impair realism [26], game experience [59] and enjoyment [26]. The provision of realistic weight sensations is therefore a key challenge for the advancement of VR.

To address this problem, researchers have shown increased interest in exploring novel interfaces that simulate the sensation of weight [33, 63]. Yet, generating realistic and robust weight forces remains an unsolved challenge, as it requires a simulation of a multitude of complex tactile and kinesthetic inputs to imitate the sensation of gravity [33]. Liquid-based weight simulation, however, can provide the perception of actual gravitational forces by adjusting the mass of VR devices and has therefore emerged as a promising technique to convey weight in VR [11, 12, 26, 34, 56]. This concept employs liquid reservoirs into handheld or body-worn devices. To change their weight, liquid is either pumped to or from external reservoirs. These reservoirs are connected via tubes and either placed stationary or worn on the back. Following the initial concept, which was meant for teaching aids in non-VR contexts [36], the technique was applied to a VR controller by Cheng et al. [12]. This initial prototype had a low pumping rate of 19.62 g/s and was only capable of rendering up to 330 g at a single body part with a single center of mass. Consequently, a range of research prototypes were created to overcome these constraints. Monteiro et al. [34] developed FluidWeight, a portable system, that uses two separate water reservoirs to represent different centers of mass. Wang et al. [56] presented VibroWeight, combining these weight adjustments with vibrotactile feedback while maintaining mobility. Chen et al. [11] introduced GravityPack, a stationary device, capable of rendering weight across four body parts. Lastly, Kalus et al. [26] introduced PumpVR, achieving high flow rates and absolute weight changes up to 1 kg across two hands.

Each of these prototypes demonstrates solutions for individual objectives, with the essential objectives [23] being the achievement of wide weight ranges [11, 26], rapid weight changes [26], the preservation of mobility [34, 56], the stimulation of multiple body parts [11, 26], and the conveyance of different weight distributions [34, 56]. However, related work pointed out that, with the current design approach, it is not feasible for one prototype to fulfill all the aforementioned objectives simultaneously, due to the interference between them [23]. In particular, the initial approach to preserve mobility – wearing the hardware along with the water supply in a backpack – limits the complexity, weight range, comfort, and pumping power. Approaches that were able to meet multiple objectives, on the other hand, hinder the user's mobility through the added weight burden or through being grounded.

The limited mobility of previous approaches is contrary to the substantial effort that is made to enable mobile VR experiences [10]. Being able to walk around freely in VR is essential for effective locomotion, cognitive map building and reducing cyber sickness [31], whereas grounded cable connections were found to disturb the experience [15, 53]. Furthermore, a broad range of VR experiences requires unhindered movement, including VR fitness training [55], sport simulations [38], or motion-based learning applications [22]. Consequently, there is a clear need for mobile weight simulation, that does not compromise on other desired objectives.

In summary, previous mobile weight interfaces are highly constrained in the weight they can render, their speed of weight change, and the complexity they allow, whereas previous systems that render higher weights are highly constrained in the mobility and movements they allow. To overcome these limitations, we present MobileGravity, a novel liquid-based weight-changing prototype that separates the weight-changing object from the liquid supply and the pump. This design addresses the trade-off between mobility and performance, with MobileGravity allowing free and unencumbered movement as well as facilitating weight changes of up to 1 kg in 235 g/s. In a study, we show that MobileGravity induces distinct weight sensations and enhances realism and enjoyment in a VR setting that permits unobstructed movement. We discuss these findings, expand on limitations, and present further advantages regarding scalability and potential integration with other haptic techniques. Finally, we propose further use cases for MobileGravity, which illustrate its advantages over previous approaches. The source code and hardware design of MobileGravity are publicly available for other researchers to build on this work[1].

2 RELATED WORK

This section provides an overview of previous approaches to simulate weight in VR and subsequently reviews work using liquid transfer to provide weight sensations. Ultimately, we conclude this section by highlighting conceptual conflicts of previous techniques.

2.1 Weight Simulation in VR

As most VR controllers only feature vibrotactile feedback, previous work explored the utilization of oscillation or visual manipulations to communicate weight metaphors. For instance, Amemiya and Maeda [1] manipulated the vibration patterns of a handheld device to communicate different weights, and Rietzler et al. [41] applied spatial offsets to the visual hand position, which causes users to lift their arms higher for heavier weights, creating an illusion of weight. Other researchers varied the button resistance of the Vive Controller [48] or cutaneous pressure on the fingertip [14] to communicate weight. However, these approaches lack the kinesthetic forces, through which weight is sensed.

Therefore, other research prototypes generated downward forces to mimic gravitational pulls, for instance through propeller propulsion [18, 21]. However, as the force must always match the direction of gravity, rotating such a device can cause visual-haptic asynchrony. Furthermore, propeller noise and wind, as well as the controller's heavy empty weight add to the problems [33]. Other approaches employed a mechanism that shifts a weight block along the controller's axis [47, 65]. This alters the weight distribution within the controller. In addition, as this creates a lever, it can also induce the impression of a changed overall weight. However, this illusion is limited through the weight of the weight block and only works when the device is held at an angle [65].

Lim et al. [33] conducted a systematic review of weight simulation techniques for VR. They highlight that comfort is a major challenge for haptic weight interfaces, as reviewed devices necessitate heavy structures that cause numbing sensations and discomfort, and can decrease the effectiveness of the weight simulation. Furthermore, they observe that due to the trade-off between simulating higher weight through heavy actuators and the ability of the user to move freely, there are no ungrounded interfaces that can simulate heavy weight. In their review, Lim et al. consider the challenge of simulating weight in VR as unsolved, as no approach could fully address the difficulty of accurately and synchronously providing a high range of weight at both hands. They argue that perceiving weight in VR accurately requires the exertion of gravity forces.

[1] https://github.com/a-kalus/MobileGravity

2.2 Utilizing Liquid Transfer to Render Weight

A method to actuate real gravitational forces is to utilize liquid mass transfer. Niiyama et al. [36] presented a weight-changing device that demonstrated this concept. Their device used a bi-directional pump to move liquid metal via a flexible tube into a bladder. This bladder was placed in a shell to yield a weight-changing object. Users could hold the weight-changing object to sense weight either in a miniature solar system, to experience the size and weight relations between different planets, or in a rectangular block demonstrating the density of different materials. A further application used the weight-changing object to actuate the movements of a lever. While not explicitly intended for VR applications, this approach laid the conceptual groundwork for integrating liquid mass transfer into human-computer interaction to convey weight sensations.

Building upon this foundation, Cheng et al. introduced GravityCup [12], which adapted the concept of liquid transfer to simulate the weight of vessels in VR. Their prototype consisted of a handheld water container and a waist-worn component, with both units featuring sealed bags interconnected by two water pumps, enabling a weight range of up to 330 grams for the handheld container. The apparatus weighs 1500 g in total and 330 g can be pumped from the wearable device to the handheld device (or vice versa) in 16.8 seconds. Users can carry the handheld device to experience the weight of virtual vessels (i.e. a coffee mug, a watering can, and a bowl of dog food) that are gradually filled or emptied, for instance, while watering plants or pouring coffee. A fourth scene depicts the user holding an empty cup, while objects floating in the virtual room indicate changes of gravity. However, the use of the device for other applications is limited by the perceptible liquid inertia and the slow rate at which the weight adapts (19.62 g/s).

Similarly, FluidWeight, presented by Monteiro et al. [34] transfers water (500 g) between a body-worn container and a handheld device at a rate of up to 66 g/s. Expanding on GravityCup, the system employs three water balloons in the handheld unit to change the center of mass in one dimension. Two water pumps, two stepper motor-driven syringes and two solenoid valves are incorporated to transfer water from a backpack via six hoses to the handheld device. To achieve varying centers of mass the water balloon located at the front of the device is controlled by the syringes, while the balloons at the back of the device are controlled by the pumps. However, the change in weight distribution can only be applied in one dimension. A VR fishing game demonstrated the application of the system.

Moreover, Wang et al. [56] advanced this concept of liquid-induced alterations in weight distribution and absolute weight by adding vibrotactile feedback, resulting in VibroWeight. Similar to FluidWeight, VibroWeight consisted of a backpack connected to a handheld device containing two water balloons. The device utilized two 42-step motors, each controlling a syringe to displace water or liquid metal. In an evaluation, VibroWeight actuated absolute weight changes of 10 g, 20 g, 30 g, 40 g, and 50 g. The flow rate was not specified. A user study showed, that VibroWeight increased the user's realism and comfort when interacting with a water gun, a sword and stones in a virtual environment. As with FluidWeight, the shift of center of weight was one-dimensional and could only target a single body part.

Enhancements regarding flow rate, weight range and single-handedness were achieved by Kalus et al. [26]. Their prototype PumpVR encompassed a water supply and two controllers, each containing a 500g water bag. Solenoid valves were incorporated to enable concurrent or independent weight changes of the handheld controllers. The integration of a high-performance bi-directional pump enabled this system to realize a flow rate of 150.8 g/s and absolute weight changes of up to 1 kg (500g per hand). In a user study, PumpVR was shown to increase realism and enjoyment during the simulation of various objects, and to enhance virtual embodiment when used to convey body weight. Yet, with the added structural complexity and overall weight, PumpVR was placed stationary during the VR experiences, limiting users' mobility.

To increase the number of stimulated body parts, Chen et al. [11] introduced GravityPack, which involves the attachment of water bags to up to four body parts. This system allowed for absolute weight adjustments totaling up to 1.36 kg, distributed across various limbs. The waiting time for the completion of the weight adjustment can last up to 40 seconds with a flow rate between 39.2 g/s and 46.9 g/s. Visualisation methods to bridge the waiting times were explored in a VR game where players watered carrots and pulled them out, and fed them to rabbits. The integration of multiple water containers, solenoid valves, and pumps greatly increased the weight and structural intricacy of GravityPack. Therefore, it cannot be worn on the back, restricting users from walking around freely.

2.3 Summary

Simulating gravity forces to convey weight has proven challenging in terms of accuracy, mobility, comfort and conveying heavy weights [33]. Therefore, numerous devices were explored, that use liquid mass transfer to render actual mass [11, 12, 24, 26, 34, 36, 56]. These prototypes have addressed individual objectives, some of which conceptually conflict with each other. Most notably, previous designs do not allow for lightweight and mobile prototypes without compromising on flow rate and range of weight that can be rendered [23]. Consequently, the present approach to mobile liquid-based weight simulation needs to be revised through novel design considerations.

3 SYSTEM

We developed MobileGravity, a system, where the weight-changing object is separated from the liquid supply and the actuator. It removes unintended weight loads from the user and thus allows for integrating powerful actuators and high-volume water reservoirs, while also permitting free movement. MobileGravity consists of a mobile handheld proxy object and a base station that can deliver up to 1 kg into the proxy object at a flow rate of 235 g/s. Both components are depicted in Figure 2.

3.1 Concept

Central to our design is the integration of quick disconnect couplings to connect and disconnect the handheld device to the water supply whenever its weight needs to change. The quick couplings embedded in our design are Koolance QD3 Quick Disconnect No-Spill Couplings, which are fittings that automatically cut off the

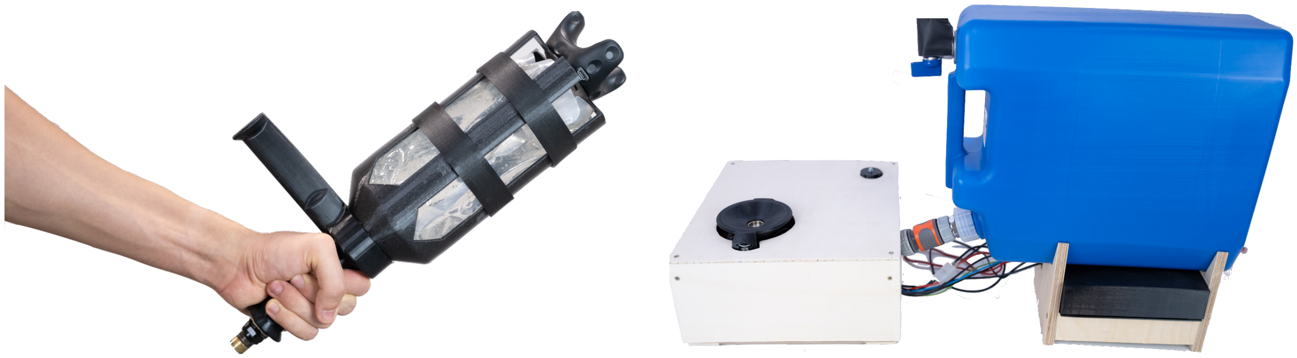

Figure 2: The handheld proxy object (left) and the base station (right).

water flow when disconnected. The male fitting [2] is integrated into the proxy object, while the corresponding female fitting [3] is embedded in a dedicated box connected to the water supply, hereinafter referred to as base station. The weight adjustment process is initiated when the user aligns the handheld proxy object with the base station and engages a single push to facilitate the coupling of both fittings. To preserve immersion, this alignment is carried out within the virtual environment, through the user's act of placing a virtual object at a designated location. After changing the weight, solenoids pull down a safety ring so that the proxy object is decoupled again.

Moreover, the proxy object features a secondary handle positioned perpendicular to its primary handle. This additional handle allows users to experience a different center of mass when picking up the proxy object after the weight change. Depending on the handle and grasp angle, users can perceive the center of weight at various positions, including the top, bottom, front, back, left, or right of their hand, substantially increasing the number of objects that can be simulated.

The user's hands are constantly tracked and displayed, enabling users to interact with the virtual world when the proxy object is set down. As a result, MobileGravity can also serve as a complementary device rather than a mere replacement for other input devices. Hand tracking is enabled through cameras integrated into or attached to the VR headset, such as the Leap Motion Controller.

3.2 Handheld Proxy Object

To enable a wide range of weights, we incorporated a flexible water bag with a 1-liter capacity (Recreatio, 247Goods), a larger version of water reservoirs employed in previous controllers [26]. Due to their flexibility, the water bags contract under negative pressure and resize with the amount of water they contain, preventing liquid inertia. We 3D printed a PETG housing to encase the water reservoir with key considerations for lightweight and stability. The housing features vertical gaps, serving two essential purposes: minimizing the empty weight and providing visual feedback on the fill state of the water bag. Two 3D-printed TPU rings surround the housing to hold the water bag in place.

A HTC Vive Tracker screwed onto the top of the housing enables positional and rotational tracking. The water reservoir is connected to the male fitting via a flexible tube running through the proxy object's primary handle. The primary handle and the secondary perpendicular handle are 3D printed as a single piece, which is screwed to the housing via built-in threads. The empty weight of the proxy object is 457 g (for comparison, the HTC Vive controller weighs 203 g). As a result, it can render weights from 457 g to approximately 1460 g.

3.3 Base Station

The base station consists of a box with a recess at the top from which the female connector protrudes. We extended the safety ring of the female fitting with a funnel-shaped PETG socket. The socket has a slope towards the fitting in the center so that the proxy object can snap in smoothly. The base station's coupling mechanism leverages two 12 V (DC) solenoid actuators, calibrated to pull the safety ring and disconnect the proxy object when needed. We installed a limit switch that detects the position of the safety ring to determine whether the proxy object is currently connected to the base station. According to the manufacturer's specifications, the quick couplings have leakage of approximately 200 μl per ejection[4], so we embedded a drip tray underneath the socket. The water is moved by a Marco UP1-JR 12V pump [46], previously demonstrated to exhibit high performance in similar applications [26]. The pump has a flexible rubber impeller to change the direction of water flow. It is connected to a 10 l water tank, with the connection placed below the fluid level. We have chosen such a high capacity so that one base station can supply several proxy objects, enhancing the system's scalability and accommodating the needs of multiple users or two-handed scenarios. The water tank further includes a vent line to permit air entrained in the fluid to escape. The base station can be tracked using either the tracked position of a coupled proxy object or by attaching another Vive tracker.

[2]https://koolance.com/qd3-ms13x19-bk-quick-disconnect-no-spill-coupling-male-for-13mm-x-19mm-1-2in-x-3-4in-black

[3]https://koolance.com/qd3-fs13x19-bk-quick-disconnect-no-spill-coupling-female-for-13mm-x-19mm-1-2in-x-3-4in-black

[4]https://koolance.com/qd3-ms13x19-bk-quick-disconnect-no-spill-coupling-male-for-13mm-x-19mm-1-2in-x-3-4in-black

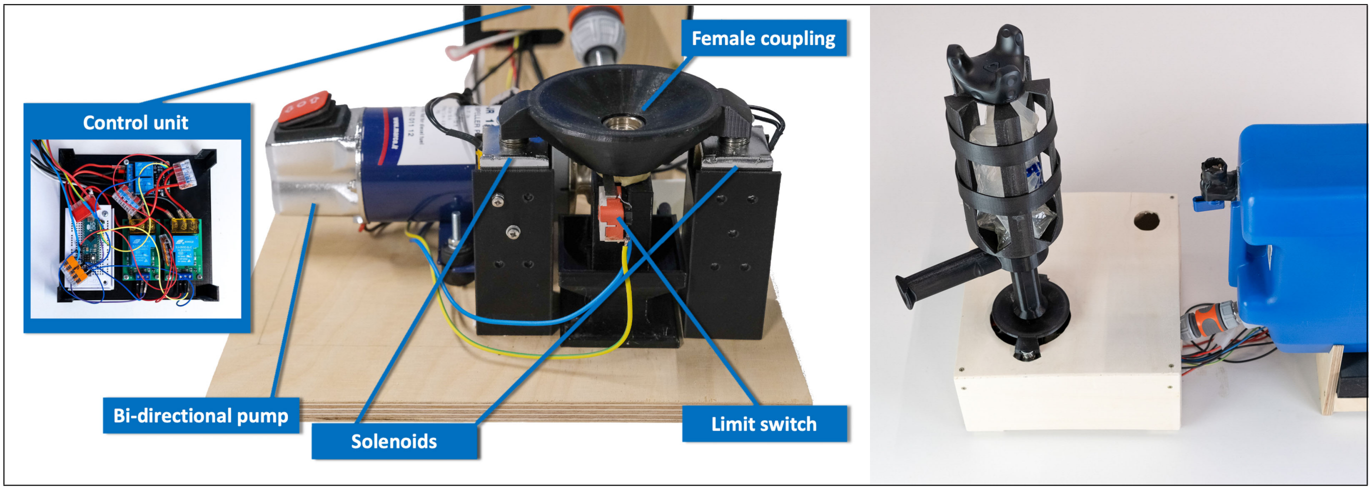

Figure 3: Components and inner mechanics of the base station (left) and the established connection between the base station and the proxy object during the weight change (right).

The various components are controlled using an Arduino Micro microcontroller, which operates four single pole double throw relay modules and reads out the limit switch. Two relay modules switch the solenoid actuators to eject the proxy object. The other two relay modules, wired as a polarity switch, are used to stop or start the pump and determine its direction. The Arduino continuously reads the limit switch to determine if a water connection between the base station and the proxy object is established. Figure 3 shows how this connection is set up and depicts the components and inner mechanics of the base station.

3.4 Control Logic

Serial communication between the Arduino Micro and the game engine Unity is established through a USB connection. We used the SerialPort class in the .NET Framework. Commands sent by Unity trigger the weight change and define the pumping direction, as well as the weight to be transferred. One of ten 100 g multiples can be targeted, with 100 g translating into a pumping duration of 425 ms. Hence, the game engine calculates the difference between the previous and target weight and prompts the Arduino to run the pump for either 425 ms (100 g), 850 ms (200 g), 1275 m (300 g), 1700 ms (400 g), 2125 ms (500 g), 2550 ms (600 g), 2975 ms (700 g), 3400 ms (800 g), 3825 ms (900 g) or 4250 ms (1000 g). The game engine can track the weight states of multiple proxies individually, based on the IDs of the Vive trackers and their positions during the weight adjustments. The Arduino notifies the game engine when the weight adjustment has been completed, i.e. when the selected pumping duration has passed. The game engine, in turn, triggers the Arduino to decouple the connectors. In our application, the decoupling is automatically initiated once the pumping duration has elapsed. The Arduino continuously sends the state of the limit switch to the game engine, to capture the event of the user returning the proxy object. Unity can use the tracked hand positions to detect the user touching the proxy object and initiate subsequent actions, such as starting the pump or ejecting the proxy object.

3.5 Virtual Test Environment

To evaluate our system, we created a virtual test environment within Unity. We chose a virtual workshop setting, to feature objects with a broad range of weight while engaging the user in a coherent scenario. We used assets from the Garage Workshop package, which is available from the Unity Asset Store[5]. For the hand tracking integration we used the Leap Motion Controller and the Ultraleap SDK for Unity.

Figure 4: The six different tools that the user can interact with in the virtual environment.

The scene features six tools of different weights, which we chose to match the weight of real tools, while ensuring consistent weight differences between them: An approx. 460 g paint roller, an approx. 660 g stapler, an approx. 860 g hammer, an approx. 1060 g hacksaw, an approx. 1260 g blowtorch, and an approx. 1460 g cordless drill. Note that the weights listed include the proxy object's empty weight of 457 g. The tools are shown in Figure 4. Furthermore, the scene includes two tables – a tool bench and a worktable – placed two meters apart, each with a blackboard on it. A 3D model of the extended female connector is embedded in the tool bench and its position matches the position of the female connector in the real world.

Users can interact with the virtual tools to build a bird box based on a guide from the Royal Society for the Protection of Birds [44]. The bird box takes approximately 5 minutes to complete. It is assembled in six steps, each covering a construction stage: 1. Sawing

[5]https://assetstore.unity.com/packages/3d/environments/urban/garage-workshop-104604

Figure 5: Overview of the virtual environment (left) and user's point of view (right).

the pieces of wood, 2. Drilling the holes, 3. Nailing the pieces together with the hammer, 4. Flaming the wood with the blowtorch, 5. Painting the house with the paint roller, and 6. Stapling a rubber hinge onto the roof of the bird box. Each step requires the user to first pick up the respective tool from the tool bench. To ensure that users grasp the proxy object by the correct handle (the one corresponding to the center of mass of the virtual tool), the grip of the tool is highlighted until it is picked up. Users then have to take the tool to the worktable, where they find the bird box prepared for the respective construction stage. There they use the virtual tool to carry out the work required at the current construction stage, moving it in the same way as they would a real tool. They then return the tool to the bench, which initiates the weight change and starts the next step. To enable the user to connect the proxy object to the base station in the process of placing their virtual tool, the virtual tool is temporarily extended with a 3D model of the male fitting, when users are about to return their tool. Figure 6 illustrates the first of the six steps.

During each step, users are given short instructions via the blackboards. These are prompts to pick up the respective tool (e.g. "Please grab the saw from the workbench"), familiarize themselves with the tool (shown for 10 seconds; e.g. "Observe the saw while moving it around a little."), complete the construction stage (e.g. "Saw the board along the drawn lines"), and return the tool ("Excellent! Now put your tool back to where you picked it up.").

4 EVALUATION

To evaluate MobileGravity, we conducted a user study comparing the system to a regular VR controller. The study received ethics clearance according to our institution's ethics and privacy regulations.

4.1 Method

In the study, we assessed realism, weight perception and enjoyment as dependent variables. We used System as within-subjects variable, with the two levels *standard* and *MobileGravity*. In the *MobileGravity* condition, participants used MobileGravity to complete the birdhouse scene, as detailed in section 3.5. In the *standard* condition, they instead used a regular VR controller (an HTC Vive controller). To grab and return the virtual tools in the *standard* condition, participants could simply pick up the Vive controller from a designated place on the table and lay it back again. The order of the two conditions was counterbalanced across all participants.

4.1.1 Measures. In line with previous work on weight interfaces [26], we quantified realism using the reality judgment subscale from the Reality Judgment and Presence Questionnaire (RJPQ) [5] and assessed enjoyment using the interest/enjoyment dimension of the Intrinsic Motivation Inventory Scale [45]. The reality judgment subscale comprises eight items relating to realism, presence, and reality judgment, ranking from 0 to 10. The interest/enjoyment subscale asks participants on 7-point Likert items to rate their agreement with seven statements. To investigate the weight perception we adopted the questionnaire by Stellmacher et al. [49], which was previously used to assess subjective weight perception. We replaced the word "cube" with "object". After excluding task-specific items, a set of five questionnaire items emerged, addressing effectiveness ("I experienced different weights during the task."), efficiency ("I could quickly determine whether the objects were of the same or of different weight."), haptic realism ("Differences in weight of the virtual objects felt the same as differences in weight feel in the real world."), grasping effort ("In tasks where I perceived one object to be heavier than the other, I had to grasp the heavier object more firmly than the lighter one."), and lifting effort ("In tasks where I perceived one object to be heavier than the other, I had to put more effort with my arm into lifting the heavier object than the lighter one."). The questions are scored on 7-point Likert items. Additionally, we collected qualitative feedback using an open-ended question, which asked whether participants perceived any differences between the two versions in terms of realism, and if so, which ones.

4.1.2 Participants. 31 participants (19 identified as male, 12 as female) aged between 20 and 31 years ($M = 23.61$, $SD = 2.88$) were enrolled in the study. One participant was excluded from the analysis due to a technical error with the hand tracking system. Recruitment took place through institutional mailing lists. Inclusion criteria necessitated normal or corrected-to-normal vision. 16 participants reported never using VR, 12 used VR a few times per year and 2 used VR a few times per month. Prior to the experiment, all subjects signed written informed consent and agreed to participate. They were compensated for their involvement with 5€ or credit points for their study program.

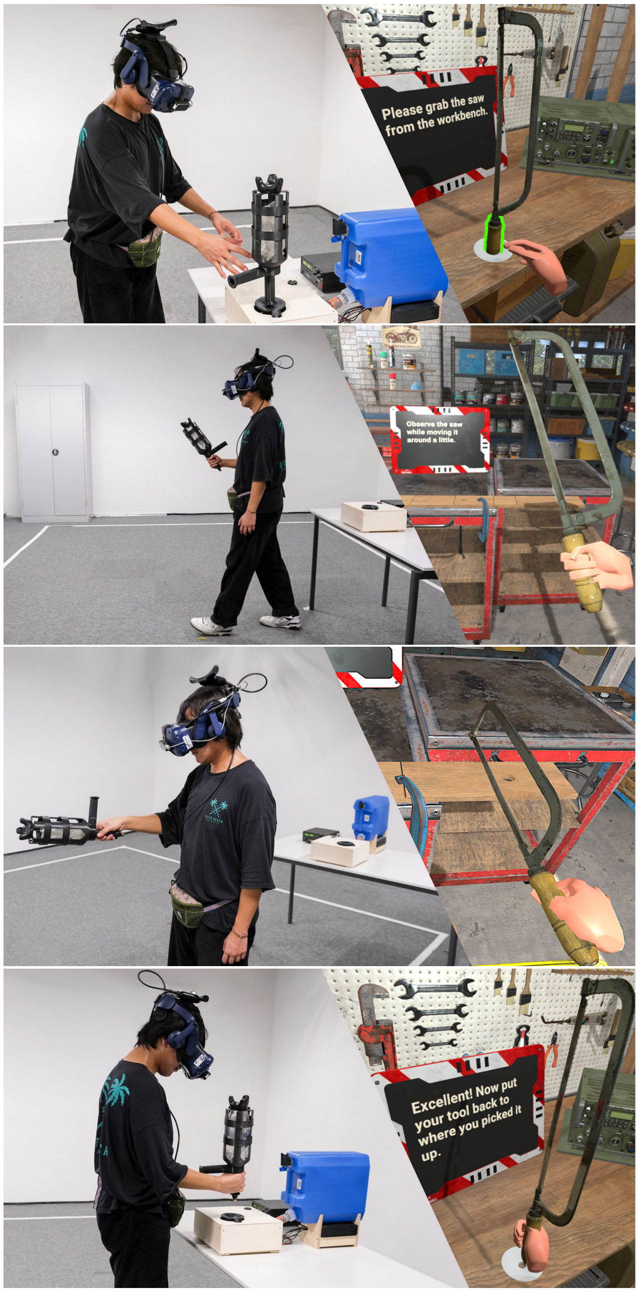

Figure 6: User picking up a virtual saw (top row), familiarizing himself with the saw (second row), working on the bird house with it (third row), and returning it (bottom row).

4.1.3 Apparatus. Participants wore an HTC Vive Pro head-mounted display (HMD) with a Leap Motion Controller attached to it to track their hands. A Vive wireless adapter connected the HMD to a desktop PC equipped with an Intel i7-8750H Processor, 16GB RAM, and an NVIDIA GeForce GTX 1060. Tracking of the HMD and VR controllers was facilitated by SteamVR Base Stations 2.0. MobileGravity's base station was powered by a laboratory power supply set at 12 V and 12.6 A and was placed on a table, which was aligned with the tool bench of the virtual scene.

4.1.4 Procedure. Participants were introduced to the study's procedure and provided informed consent in accordance with the Declaration of Helsinki (2013). Prior to entering the virtual test environment, the interaction technique of the system used in the current condition was explained to them. In the *standard* condition, they were informed that they can return their virtual tools by simply laying the Vive controller on a designated spot on the table, whereas in the *MobileGravity* condition they were shown to insert the proxy object into the base station. They then put on the HMD and completed the construction of the virtual bird box, as described in section 3.5. After each condition, they answered the questionnaires assessing realism, weight perception and enjoyment on a desktop PC. After finishing both conditions they were handed out an additional questionnaire, which asked them to provide qualitative feedback and demographic data. The experiment took about 20 minutes to complete, with about 10 minutes spent in VR (5 minutes per condition).

4.2 Results

We initially analyzed our quantitative questionnaire data to investigate the impact of MobileGravity on the VR experience. Subsequently, we analyzed the qualitative data to gain a deeper understanding of these results.

4.2.1 Quantitative results. We obtained a total score for *realism* by adding up the items of the Reality Judgment subscale. To determine the scores for *enjoyment* and *weight perception*, we averaged the ratings of their corresponding questionnaire items. We used Shapiro-Wilk Tests to verify the assumption of normality for our data. The results indicated normality for *weight perception* and its dimensions *effectiveness*, *efficiency*, and *haptic realism*. For these variables, we conducted two-tailed paired samples t-tests. The Shapiro-Wilk Tests suggested a deviation from normality for *realism*, *enjoyment*, and the weight perception dimensions *grasping effort* and *lifting effort*, for which we therefore performed Wilcoxon signed-rank tests.

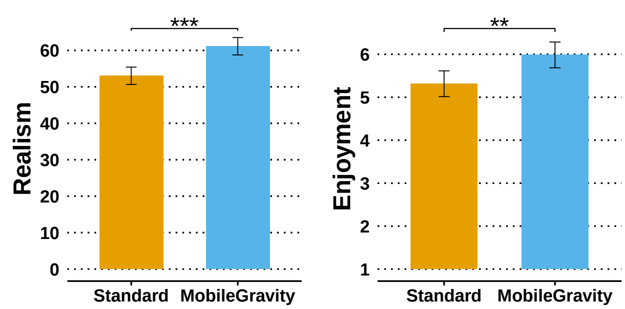

Figure 7: Mean scores of realism and enjoyment for the standard controller and for MobileGravity. The error bars show the within-subject 95% confidence interval. Asterisks denote significant differences ($p < .01$, *** $p < .001$).**

The participants rated the realism of the experience significantly higher with *MobileGravity* (M = 61.13, SD = 10.01) compared to the *standard* condition (M = 53.03, SD = 12.88), W = 23.0, $p < .001$, with a large effect of System, r_B = -0.894. There was also a large effect of System on enjoyment, W = 40.5, p = .001., r_B = -0.751, with participants indicating greater enjoyment with *MobileGravity* (M = 5.99, SD = 0.85) compared to the *standard* condition (M = 5.31, SD = 1.39). Figure 7 depicts the mean scores of realism and enjoyment.

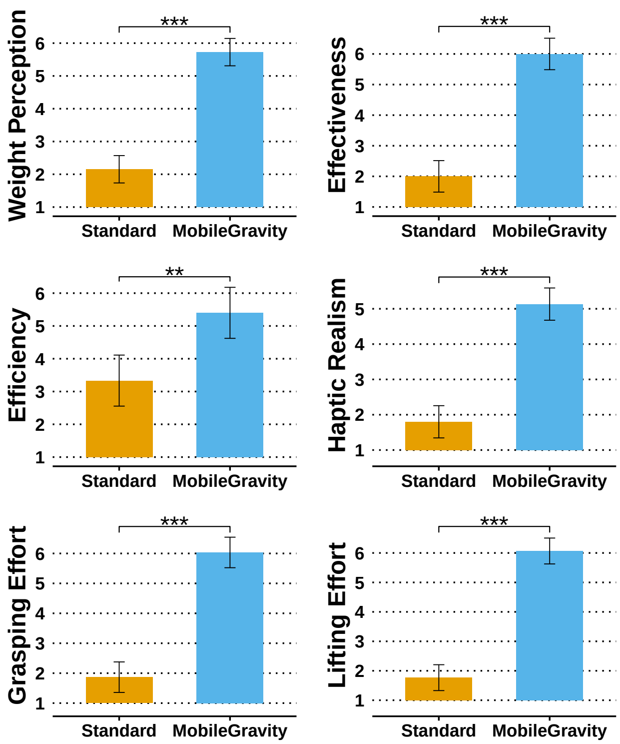

Figure 8: Mean scores of weight perception and its subscales for the standard controller and for MobileGravity. The error bars show the within-subject 95% confidence interval. Asterisks denote significant differences ($p < .01$, ***$p < .001$).**

Regarding weight perception, *MobileGravity* received significantly higher scores (M = 5.73, SD = 1.22) than the *standard* controller (M = 2.15, SD = 1.05), $t(29)$ = -12.389, $p < .001$, with a large effect of System, d = -2.265. There was a medium effect on efficiency, $t(29)$ = -3.841, p = .002, d = -0.701, and large effects on the other aspects of weight perception, which were effectiveness, $t(29)$ = -11.249, $p < .001$, d = -2.054, haptic realism, $t(29)$ = -10.561, $p < .001$, d = -1.928, grasping effort, W = .0, $p < .001$, r_B = -1.0, and lifting effort, W = .0, $p < .001$, r_B = -1.0. Figure 8 depicts the mean scores of weight perception and its dimensions.

In summary, the utilization of MobileGravity compared to a standard controller consistently demonstrated statistically significant effects across all measures. Rank-biserial correlation and cohen's d values indicate large effect sizes for these differences, except for efficiency with a medium effect, implying a meaningful practical significance.

4.2.2 Qualitative Feedback. 29 participants reported perceiving a difference in realism between the two conditions. Of those, 26 explicitly attributed this to the weight adjustment: E.g. "*[MobileGravity] felt a lot more realistic since the weight changed according to the different tools, while the [regular VR controller]* did not." (P6). The remaining three subjects also expressed that they found the *MobileGravity* condition more realistic, but either did not specify reasons (e.g. "*[MobileGravity] felt more like the real world.*" (P28), or provided elusive reasons ("[...] *because the tools felt more real*", P20). No participant considered the *standard* condition as more realistic. Moreover, no participant indicated that the coupling mechanism affected their experienced realism. Likewise, none of the participants reported any sensation of liquid inertia or hearing any associated sounds. P19 misperceived a better image quality for MobileGravity condition: (*"[MobileGravity] had the different weight which seemed a lot cooler and more interesting to me and the picture quality was quite better(?).*"

Participants also commented on the allocation of weights to the different tools in the *MobileGravity* condition. Two reported that they perceived the different weights as realistic ("*It was a very realistic change of weight between the different tools*" (P15), "*[MobileGravity] felt more realistic due to the varying and realistic weights*" (P13)), while two other participants stated that specific tools did not match their anticipated weight: "*The saw seemed a bit heavy to me, but maybe because it was the first one*" (P5), "*The version with the "weighted" controller generally felt more real, but I noticed with some tools that the weight did not match that in the real world or that the weight distribution did not match that in the real world (e.g. with the drill)*" (P11). P12 considered that possibly due to their grip characteristics, some of the lightweight tools were better represented by the Vive controller (*"... [MobileGravity] was more realistic. However, I felt some tools more realistic in [the standard condition], i.e. a painting tool and a stapler. Maybe because how tool's grip feels like is closer with that controller.*").

Six participants noted that MobileGravity affected the way they handled the tools to construct the birdhouse: "*Each tool [in MobileGravity condition] had a different feel and required another mode of handling.*" (P16), "*... because of the weightchanging controllers design I had to hold the controller as I would hold the tools.*" (P7). P16 felt that using the Vive Controller broke the immersion: "*The immersion in the [standard condition] was broken because using each tool just felt like using the same VR-controller. The tasks [...] felt much more repetitive for this reason.*"

5 DISCUSSION

Hereinafter, we discuss the insights from our evaluation and draw out their implications. Furthermore, we reflect on future work and consider the strengths and limitations of MobileGravity.

5.1 Findings of the Study

Using MobileGravity had a significant effect on weight perception, demonstrating that participants sensed the weight of the handheld proxy object and perceived it as the weight of the virtual object held in VR. This finding aligns with the unity assumption, which posits that our perceptual system interprets two distinct sensory signals as emanating from a single multisensory event [58]. The effects on the dimensions efficiency and effectiveness, as well as qualitative feedback indicate that the participants not only perceived MobileGravity's proxy as having a different weight than the standard controller but also perceived the weight to have changed.

The effect on haptic realism, which assessed if the weight differences between the tools felt the same as in the real world, suggests that they were more under the impression that these weight differences matched the differences between physical tools when using MobileGravity. This was further corroborated by qualitative feedback. However, two participants reported that certain objects did not match the expected weight. To determine the appropriate weight to render, future work should consider that users have subjective expectations of an object's weight [54], which may differ from the actual weight. While it is desirable to replicate the actual weight for VR training and simulations, this may not be the case for more fictional scenarios, where users interact with objects they have less real-world experience with.

As opposed to the haptic realism scores, the mean (overall) realism score in the standard condition was notably closer to the score in the MobileGravity condition. Considering that the RJPQ takes visual aspects into account, this was to be expected, as we designed the virtual scene to mirror a real workshop and selected the task and tools to integrate seamlessly into the workshop environment. Nevertheless, we found a large positive effect of MobileGravity on the perceived realism of the participants, who attributed this to the change in weight in their qualitative feedback. This demonstrates the value of rendering object weight for a realistic VR experience. Our findings also indicated that the weight adjustments influenced how participants handled the virtual objects, as reflected by the qualitative feedback, as well as by increased grasping and lifting efforts. This provides an initial indication, that our approach may be leveraged to make virtual motor tasks more similar to real-world experiences. These implications are of particular relevance for VR training applications aiming for psychomotor skill acquisition [22]. The participants' statements regarding adjusting their movements to the tools provide a first indication that our approach may be leveraged for VR training, as the specifics of a practiced movement, (such as the angle of a tool) need to be recalled for successful psychomotor skill development [7]. MobileGravity's positive effects on (overall) realism and haptic realism are also promising in that regard, as the fidelity of the haptic device [22] and of the environment [7] are further key factors that influence the success of skill transfer. In addition, MobileGravity's effect on the enjoyment scores suggests increased intrinsic motivation for users of MobileGravity [45], which is a further driving factor for motor learning [60]. Nevertheless, further investigation is required to verify the effectiveness of MobileGravity for VR training.

As participants had to exert more effort when using MobileGravity due to the adjusted weight, the effects on grasping and lifting effort were expected. This increased effort, however, did not diminish the overall enjoyment of the experience. In fact, participants reported greater enjoyment when using MobileGravity compared to the standard controller. This is in line with previous work, which has shown that simulating the weight of objects can enhance the enjoyment of VR games [26]. Our results expand on this prior insight by exhibiting its applicability beyond gaming contexts and towards constructive tasks. Our findings further suggest that the process of inserting the proxy object into the base station to switch between objects did not cause an apparent detraction from the users' enjoyment.

5.2 Future Work and Limitations

MobileGravity's design is scalable, offering the flexibility to integrate liquid reservoirs with higher capacity or more potent actuators, without compromising on comfort or other objectives. This allows future work to further increase the flow rate, enhancing the system's ability to render weight changes quickly, or to further increase the weight range, allowing for even heavier weights to be perceived. Typical by-products of powerful actuators are noise and vibrations, which previously posed challenges regarding immersion [33]. While the participants' feedback did not indicate negative effects in that regard, this may not apply to all VR scenarios. MobileGravity's separated design however, allows to embed actuators in extensive insulation, as adding weight and bulkiness to the base station is less critical than adding weight and bulkiness to the user's body. Furthermore, MobileGravity can supply multiple weight-changing proxy objects subsequently, supporting double-handed or multiplayer VR scenarios. Accommodating additional outlet sockets could expand its applicability, supporting synchronous weight adjustments for multiple proxy objects.

Beyond weight, an optimal haptic experience involves additional types of haptic feedback. Consequently, numerous haptic devices have been developed that focus on providing collision feedback [40], changing their shape [51], or modifying their air resistance [66]. However, devices that successfully provided high fidelity feedback are limited in their adaptability to other contexts [35]. It is therefore one of the main challenges of haptic interfaces to combine the provision of different object properties [57]. Our design removed bulky structures from the weight-changing object, which opens up possibilities for combining various types of haptic feedback in a single handheld device. It seems feasible, for example, to incorporate the connector and liquid reservoir from MobileGravity's handheld proxy into other haptic devices, which could be a promising area for future research.

An inherent limitation of tubeless designs is, that they don't provide mobility to experiences, in which the weight should be perceived as gradually increasing, such as filling a virtual cup of coffee [12], or when weight is intended to change unexpectedly, such as when a fish bites in a fishing game [34]. In these cases, users must forgo mobility and temporarily connect a hose equipped with compatible quick couplings between the units. Moreover, users of MobileGravity have to return the proxy object to a fixed spot to change its weight, which poses restrictions for the design of the virtual scene. Even though the process of connecting both components for the weight change did not seem to distract the users in the use case tested, this may vary in other use cases. We expect the best acceptance when the base station is embedded in the virtual environment and the need for placing the proxy is contextualized within the narrative of the application. If the design of the virtual world does not allow to seamlessly integrate the base station interaction in a meaningful way, one solution could entail having the user open a menu to change objects. This menu would pause the application, comparable to inventory menus found in games such as Skyrim VR [50], with the difference that the menu is a spatial environment and the user interacts not only with a GUI but also with the MobileGravity base station, whose virtual counterpart is displayed when the menu is opened. Beyond this, promising solutions

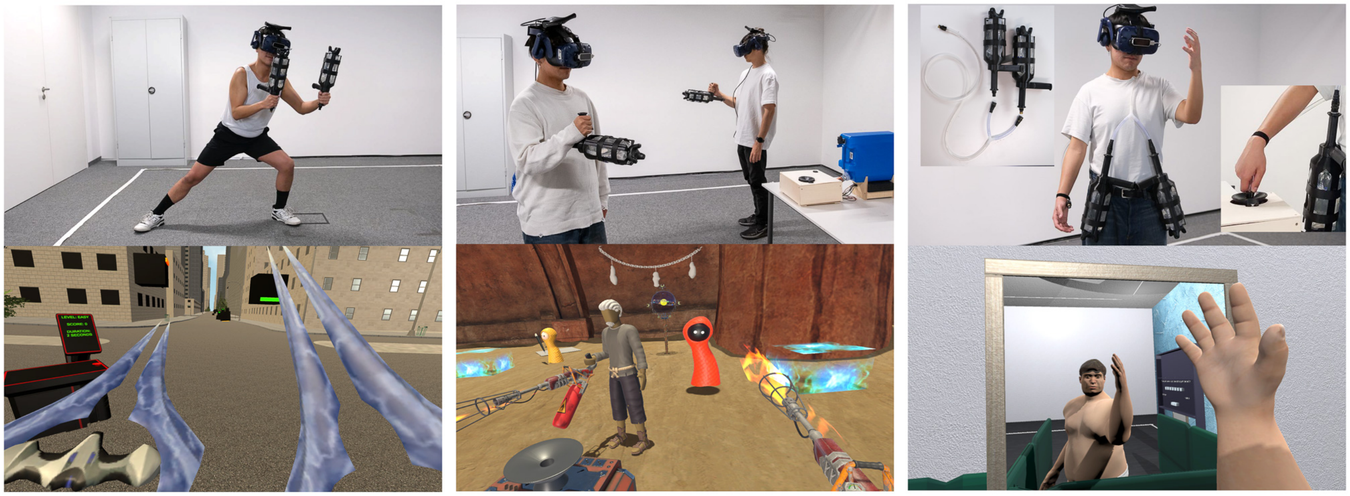

Figure 9: Setup (top) and VR view (bottom) of the use cases. The left column shows the VR workout, the middle column depicts the co-located VR game, and the right column illustrates the avatar weight simulation.

could consist in techniques, such as redirected walking [32, 37, 42], haptic retargeting [3, 64], and redirected placement [62], that unnoticeable manipulate the virtual world or the avatar, causing users to unconsciously adjust their movements to compensate for these alterations. This allows for the redirection of users' movements to a specific destination in the real world, while giving them the impression that they have headed towards a different spot. As such illusions have been used to assign a single VR proxy to multiple counterparts in different locations in the virtual environment [3], or to retarget placement tasks [62], its utilization to subconsciously redirect MobileGravity users to the base station could be explored in future work.

Overall, MobileGravity seems best applicable when increased realism and prolonged physical interactions with varied-weight objects is essential and prioritized over easy virtual object handling. Participant feedback, as well as increased grasping and lifting effort, indicates that sensing weight using MobileGravity introduced a higher physical demand compared to regular controller use. This is important to consider when designing for scenarios where the interaction mimics real-world tool use but where ease of use is more critical than strict realism. One example of such a use case is a VR 3D design application in which users shape landscapes using a virtual shovel. In this example, the goal of creating the landscape effortless may take priority over the realism of the shovel, thus making the use of MobileGravity to sense the shovel's weight impractical. In this context, it is crucial to recognize that MobileGravity does not intend to entirely substitute conventional VR controller interactions. In phases where perceiving weight or connecting MobileGravity's components is inappropriate, users can interact with their tracked hands or even pick up regular controllers while the proxy object remains in the base station until the VR scenario necessitates the sensation of weight, at which point the user can then pick up the proxy object.

6 FURTHER USE CASES

Beyond its application in the simulation of power tools, we provide further use cases for MobileGravity, that were not possible using previous systems. In addition, they showcase MobileGravity's double-handed use, the sharing of a single base station by multiple co-located users and reconfiguration capabilities to sense the weight at other parts of the body.

6.1 Unhindered VR Workout

Fitness VR applications gained considerable traction, with numerous applications leveraging the immersive nature of VR to enhance workout experiences (e.g., [13, 20, 61]). In this context, adding physical weight to intensify the VR workout experience has become a demand, leading to the practice of placing weight plates inside VR controllers before exercising in VR [4]. Using such accessories requires a cumbersome process of manually reassembling the controllers each time the weight needs to be changed. Employing MobileGravity's weight adjustments enables to smoothly change workout intensities without interrupting the VR experience. MobileGravity enables a wide range of exercises, which were not possible in previous prototypes, where users were constrained by tubes or backpacks, for instance, exercises that involve lying down, running or turning.

In our sample use case, the user is immersed in a stylized urban environment while holding two MobileGravity proxy objects, one in each hand. The objective is to hit objects of different colours that emerge from the background, similar to popular applications, such as VR Workout [61], Beat Saber [19], and FitXR [13]. To destroy the objects the right timing, angle, and position is crucial, which is why the activities require the user to take different stances, or even lie down. The proxy objects are visualized as sci-fi blades, with their volume corresponding to the physical weight of the proxies. After completing an exercise, users go to a terminal where they can see their fitness statistics. They then change their blades by inserting

[4]https://www.kiwidesign.com/products/vr-dumbbell-for-oculus-quest-2

their proxy objects subsequently into the base station, which is integrated into the terminal in the virtual world. The weight of the proxy object is thereby adjusted to accommodate to the user's fitness level or to switch between fast-paced, lightweight scenarios and more deliberate, heavyweight scenarios for strength training.

6.2 Heavy and Lightweight Game Items in Co-Located Room-Scale VR

VR games often revolve around presence, the feeling of "being there" [8]. Both object weight simulation [56] and natural walking [53] can significantly amplify the sense of presence. In our exemplary action game, players walk around the game world and defeat enemies. It can be played in single-player mode or collaboratively, in a co-located multiplayer mode, where multiple users in the same room can take turns connecting their proxy object to a single base station. Players can equip themselves with a variety of items. However, instead of pressing a button to open the menu to change their equipped item, as, for instance, in Skyrim VR [50], they insert their proxy object into the base station. They can then select an item using their tracked hands, after which MobileGravity adjusts the weight of the proxy object accordingly and ejects it. During the game, players can choose between heavy weapons that deal more damage or lightweight weapons that are easier to handle. Certain types of enemies require a specific item to be beaten. For instance, ice blocks require a flamethrower, whereas ghosts need a wand.

6.3 Avatar Weight Simulation with Unrestricted Movements

When embodying an avatar in VR from a first-person perspective, users experience the virtual body as their own. This sensation is leveraged by VR designers to enhance game experiences, develop VR tools for psychotherapy, or to study perceptual aspects of body ownership [25, 28, 43]. There are, for example, clinical applications, in which a strong sense of embodying avatars with different body weights is required, to reduce fear of weight gain in anorexia nervosa patients [6]. While using liquid transfer to simulate body weight has demonstrated efficacy in enhancing the sense of embodiment, the existing method is limited to stationary scenarios and restricted body movements and orientations [26]. However, embodied experiences frequently involve the user moving freely in front of a virtual mirror [4, 17, 27, 30], as experiencing control over the avatar's actions amplifies the sense of embodiment [52]. Unrestricted movements are particularly essential in scenarios, where the movements when embodying different avatars, such as walking, are subject of analysis [29, 39].

MobileGravity allows users to embody avatars of different weights while freely navigating the VR space, gaining a new set of scenarios. MobileGravity's modular design enables options to reconfigure the system. In our use case, users wear two proxy objects on their body using a strap. Two female quick disconnect fittings connect them to a single hose, which leads through the sleeve of the user to the hand, where a male quick connect fitting protrudes, enabling the user to connect the proxy objects to the base station. This setup and the additional y-shaped hose are depicted in Figure 9. The application adjusts the weight of the worn proxy objects in accordance with the expected body weight of the embodied avatar and decouples the user from the base station.

7 CONCLUSION

In this work, we introduced and evaluated MobileGravity, a novel mobile weight interface for VR utilizing liquid mass transfer. It overcomes previous limitations, that restricted mobile systems in the weight they can render, their speed of weight change and their complexity, and constrained heavyweight simulations from allowing freedom of movement. MobileGravity decouples its heavy components, such as the pump and the liquid supply, from the weight-changing object. This enables MobileGravity to apply weight changes of up to 1 kg in 235 g/s and yet allow users to walk around and turn in any direction. It is therefore particularly valuable to scenarios that require effective locomotion or unhindered movement. In a study, 30 participants used MobileGravity to perceive the weight of different tools during the process of constructing a bird box in a virtual workshop. This resulted in a positive impact on realism and enjoyment, demonstrating the system's ability to simulate objects of a high range of weight in mobile scenarios. Future work should explore assigning the proxy object to virtual objects located differently through the integration of haptic retargeting techniques, such as redirected placement. Additionally, larger reservoirs or denser liquids could be employed to further increase the range of weight. Finally, MobileGravity's proxy object could be integrated into devices featuring other types of feedback, such as collision feedback or shape changes.

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