# STROE: An Ungrounded String-Based Weight Simulation Device


Alexander Achberger*
Mercedes-Benz AG, Stuttgart, Germany

Pirathipan Arulrajah†
Mercedes-Benz AG, Stuttgart, Germany

Kresimir Vidackovic‡
Hochschule der Medien, Stuttgart, Germany

Michael Sedlmair§
VISUS, University of Stuttgart, Stuttgart, Germany


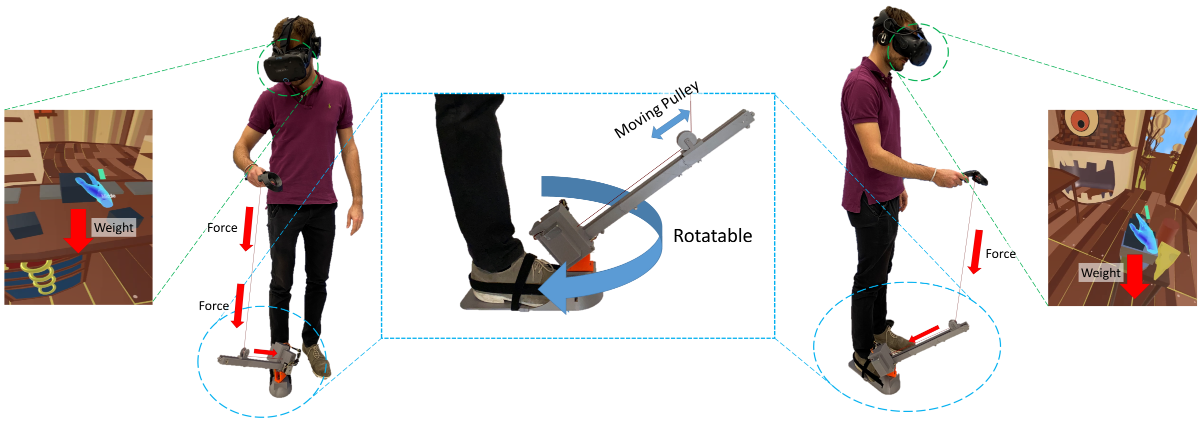


Figure 1: The use of STROE in two VR scenarios. STROE strapped to a shoe and generates downward forces on the user's controller to simulate the weight of objects. A motor pulls a string attached to the user's controller. This string is guided by a movable pulley that is mounted on a rotatable rod, allowing to generate the force downwards independent of the user's controller position.


## Abstract

We present STROE, a new ungrounded string-based weight simulation device. STROE is worn as an add-on to a shoe that in turn is connected to the user's hand via a controllable string. A motor is pulling the string with a force according to the weight to be simulated. The design of STROE allows the users to move more freely than other state-of-the-art devices for weight simulation. It is also quiter than other devices, and is comparatively cheap. We conducted a user study that empirically shows that STROE is able to simulate the weight of various objects and, in doing so, increases users' perceived realism and immersion of VR scenes.



**Index Terms:** Human-centered computing—Haptic devices—;—


## 1 Introduction

While virtual reality (VR) gives users the ability to experience the virtual environments more immersively and to interact with them more realistically, haptic feedback is still lacking in most user setups. The most commonly used haptic feedback is vibrotactile, which is triggered by the user's controller. Vibrotactile feedback can not exert forces onto the user, such as for a collision or weight simulation. Nowadays, VR users do not feel the weight of virtual objects, which can result in a less realistic and immersive experience. Additionally, weight simulation can be helpful in some VR applications, such as in the automotive industry, where our background lies in. Here, engineers can benefit from weight simulation in VR, for example in VR tasks during which they evaluate how ergonomically a certain car component can be assembled. Weight simulation of the car component can give them results that are more similar to the same physical task results. Current weight simulation devices have shown that interacting with virtual objects can feel more realistic and increase immersion with haptic feedback [14, 17].

Currently, there are few research prototypes that can simulate weight but have several disadvantages. There are grounded devices that are permanently connected to the physical environment, such as the INCA 6D [27] or Virtuose 6D [13]. However, there are many cases where the VR application needs to allow free movement and covers a larger workspace. Most grounded devices only cover a small workspace or are expensive and difficult to implement. Therefore, there are also ungrounded devices that can move independently, such as drones [4], or devices that are attached to the user's body to allow free movement during weight simulation. Current ungrounded weight simulation devices have multiple limitations such as disturbing sound [4, 14, 17], high latency [8] and weak forces [14].

Towards addressing these challenges, we propose STROE, a new ungrounded string-based weight simulation device. STROE is worn as an add-on to a shoe and consists of a motor with a pulley. One side of the string is connected to the pulley and the other side to the user's controller, hand, or tool. When the motor begins to generate torque, the string stretches and the user experiences a force that is sensed as a weight simulation. STROE's design allows most of the force to be directed towards the floor, regardless of the user's movement, in order to simulate the weight as realistically as possible. STROE can simulate a weight up to 720 g and has a latency of only 250 ms with little sound disturbance.

We conducted a user study to evaluate how precise and realistic STROE can simulate weight and how well users can walk while a weight is simulated. Our results show that all participant were able to perceive different weights with STROE. Using STROE, participants had more fun in the VR scenarios and perceived them more realistically and immersively. STROE shows potential regarding


*e-mail: alexander.achberger@daimler.com
†e-mail: pirathipan.arulrajah@daimler.com
‡e-mail: vidackovic@hdm-stuttgart.de
§e-mail: michael.sedlmair@visus.uni-stuttgart.de

mobility. As an early prototype it still has limitations regarding ergonomy, which we will discuss in the paper.

In sum, our contributions are:

- The design and implementation of STROE: A new ungrounded force feedback device for weight simulation
- Design decisions and a technical evaluation to measure STROE's specifications
- A user study with 12 participants who evaluated STROE in four different VR scenarios

## 2 Related Work

In this section, we clarify which haptic feedback devices exist that can simulate weight and how they differ from STROE. We categorized the work based on the used technology.

**Weight Illusion** In addition to providing users with real forces to simulate weight, there are some approaches that use tactile feedback to give the illusion of weight. Grabity [9] and Gravity Grabber [24] create virtual force tangential to each finger pad through asymmetric skin deformation. Kuniyasu et al. [20] use this technology on the forearm to simulate a feeling that someone is holding the users arm. Samad et al. [28] create force sensation by manipulating the control-display ratio. They render the objects position depending on the objects weight with a distance to the real position, in order to sense a harder movement when the object is heavy. Compared to STROE, however, weight illusion does not provide any real forces and therefore does not generate fatigue, which can be insufficient in some VR scenarios, such as automotive buildability studies.

**Propeller-Based** There are some devices that create forces by propeller propulsion. Thor's Hammer [14] has six propellers that can generate forces in 3 degrees of freedom (DoF) that can be used to simulate weight. Areo Plane [17] uses two propellers to provide forces to the ground and also to generate a weight shifting simulation. Wind Blaster and PropellerHand [5, 18] are devices that attach two propellers on the user's wrist, to allow free hand interactions. There are also approaches that use drones [4]. To simulate weight, they turn their propellers off to simulate it with their own weight. However, in contrast to STROE, the more force propeller-based devices produce, the more hearable noise they create (up to 93.5 dB in case of Aero Plane). As a result, they are either very loud or generate little force, which is unacceptable in some VR use cases when they need to concentrate or talk to other people. Additionally, propeller based devices have a high latency compared to STROE, due to the acceleration of the rotors.

**Liquid-Based** GravityCup [8] is a controller with a tank into which a liquid can flow to enable weight simulation. Niiyama et al. [26] also use this technique to dynamically change the size and weight of objects they can grab in VR. However, compared to STROE, this approach needs a compressor, which limits the ability to walk freely. In addition, the liquid must be carried on the back or placed in a stationary position and has a very high latency, which can be problematic in many VR scenarios.

**Electrical Muscle Stimulation** Lopes et al. use electrical muscle stimulation to provide force feedback [22]. Their system creates a counter force on the muscles that have to be used to simulate the force. Then, the users have to activate the contrary muscle. For example, to hold an object, the system triggers the triceps and the users have to use their biceps to hold the object on one height. In contrast to STROE, this system needs a long time to put on and the users are connected with multiple cables, which restricts their movement. In addition, the electrodes are difficult to place on the body.

**Shifting Weight** There are also some devices that can simulate a shift in weight for objects with a different center of mass. Transcalibur [29] is a handheld device that can change its form in order to simulate a weight shift. Shifty [30] uses a weight that is moved along a pole to simulate a weight shift. Compared to STROE, these devices can produce a weight shift, but they all have the same overall weight and are therefore unsuitable for VR applications where users have to hold objects with different weights.

**Body-Grounded** There are some devices that are attached to the user's body and move with the user. The workspace is unlimited then. SPIDAR-W [25] and HapticGear [16] are backpack-worn devices that can provide force feedback. In contrast to HapticGear, SPIDAR-W can provide 6-DOF forces on both hands instead 3-DOF on one hand. Compared to STROE, they are more difficult to put on and more uncomfortable. WireMan [7] is a backpack-worn force feedback device similar to SPIDAR-W and HapticGear. Melchiorr et al. [23] developed a one-wire version of WireMan to investigate the potential of force feedback using only a single wire. Results show, that the device allows for a detection of obstacles in the environment. However, the one-wire design of WireMan cannot generate forces to the ground. STROE's design allows to move the interacting hand without influencing the force vector.

**Grounded** The presented devices above are ungrounded devices that are either attached on the user's body or can move on their own. Yet, there are also grounded devices that are permanently mounted on the physical environment and can simulate weight. Mechanical arms like Virtuose 6D [13] use motors on joints to produce force. However, their working space is limited and not suitable for mobile usage. One of the first string-based haptic devices was SPIDAR [15] which uses multiple motors to retract strings that are connected to the user's fingers. When the user interacts with virtual objects, the motors apply a haptic feedback accordingly. However, SPIDARs workspace is small and its focus is more on collision simulation than weight simulation. INCA 6D [27] is a grounded string based haptic device with a larger workspace, but it is bulky and expensive.

## 3 Design Requirements

From related work we derived multiple requirements for the design of a weight simulation device. Additionally, we also collected requirements from our experience in the automotive industry by talking to 12 engineers who apply VR to their automotive use cases. Our collected requirements are:

- **R-Mobility**: In many VR scenarios, it is necessary to move freely and cover a large workspace.
- **R-Quiet**: Disturbing sound can decrease realism and immersion. Additionally, in some physical environments, where people need to talk to each other, loud noise may be unacceptable.
- **R-Simple**: The device should be easy to use and not take too long to set up and put on.
- **R-Latency**: Low latency is required to get realistic weight simulations instantly after grasping an object.
- **R-Price**: The price should be appropriate and not cost hundreds of dollars.
- **R-Hygiene**: Sometimes, the device is used by multiple people in a short period of time. Therefore, a thorough cleaning would take too long. Thus, there should only be a small area that is in direct contact with the user's skin.

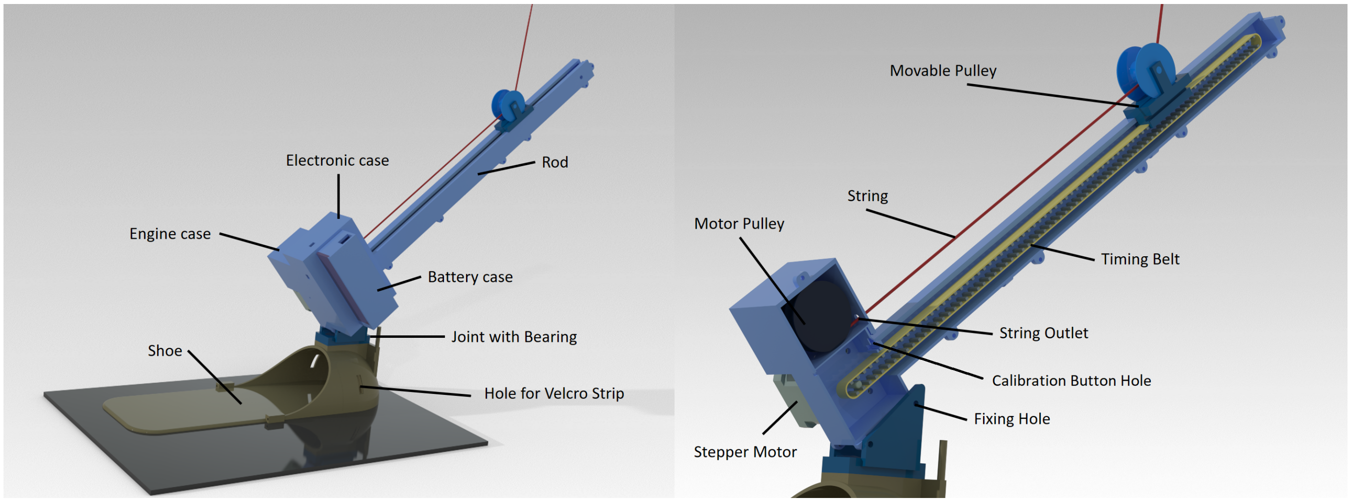


Figure 2: Left: An overview of STROE and its hardware components. Right: A close up view inside of STROE's rod.

# 4 STROE

STROE is a string-based weight simulation device, that can be attached to the user's shoe to allow free moving while perceiving a weight simulation, see Figure 2. The length of STROE's rod is 50 cm and it's height is 42 cm. The total weight of STROE is 1090 g. The total cost of all hardware components is about 150 USD. The users can place their shoe into the device and use Velcro strips to tighten it, see Figure 1. STROE is designed in a way for different shoe sizes to fit into it. Most of the components are 3D printed. The device consists of a rotatable rod where two motors are mounted on. One motor has a pulley where a string is wrapped around. The end of this string goes through a second movable pulley and is connected to the user's controller, hand, or tool, depending on what they need. When STROE applies a weight simulation to the user, it rotates the motor to generate a retraction force to the string. In order to simulate a realistic weight simulation, the force must be directed downward. Therefore, the second motor can position the second movable pulley.

## 4.1 Hardware

We used the iPower GM3506 Brushless Gimbal Motor [2] for the force simulation where the magnetic sensor AS5048A is attached to, in order to track the position of the motor's coils. To control the motor, we used as motor driver board the Simple FOC Shield V2.0.3 [3] with an Arduino Due as Microcontroller. To control it wirelessly via the computer VR program, we used a Bluetooth communication with the HC-05 module. We used a 3 cell Lipo battery with 1300 mAh to power up STROE wirelessly for about 45 minutes. The motor that moves the pulley along the rod is an ordinary bipolar stepper motor commonly used in 3D printers. We used a timing belt to move the pulley with the stepper motor, see Figure 2.

## 4.2 Pulley Positioning

To determine where to position the pulley, we attach an HTC Vive Tracker to the user's foot and measure the distance between the foot and the user's controller. In the distance calculation, we only calculate a 2D distance and ignore the height dimension and subtract an offset that is the distance between tracker and the beginning of the rod. In a first step, the pulley position calibrates by moving to the start position until it collides against a button and triggers it. To position the pulley, we used a stepper motor, where we measured 2750 steps that the motor needs to move the pulley from the start position to the end position. The distance between start and end position is 40 cm and mounted with an angle of 40 degrees, therefore the length of the rod on the 2D ground plane is $\frac{40*sin(40)}{sin(90)} = 30.64cm$.

Now we can calculate the ratio between steps and distance on the 2D ground plane with $\frac{2750}{30.64} = 89.57steps/cm$. We use this ratio to move the pulley, for example, to position the pulley to a distance of 20 cm. In order to do this, we calculate $20 * 89.57 = 1795steps$. So the motor has to do 1795 steps when the pulley is at the start position. We save this step position and update it accordingly to the controller position. Additionally, the properties of the stepper motor allow the system to hold the pulley in one position, even when a force is applied to the pulley.

## 4.3 Design Choices

During STROE's design and development process, many challenges arose that we had to solve. Here, we list our most important design choices.

### 4.3.1 Constant Torque

The most difficult challenge was producing a constant torque in order to feel a smooth weight simulation, even while moving the weight. To generate constant torque, we had to consider many aspects. The first one was the choice of a suitable motor with high torque, high precision, and low initial mechanical resistance. With initial mechanical resistance, we mean the minimal resistance to rotate the motor when it is turned off.

There are many different motor types such as stepper motors, servo motors, DC motors or brushless DC motors (BLDC). Stepper motors and servo motors have a high initial mechanical resistance, which would restrict the user's freedom of movement, since they have to apply a high force to rotate the motor, even when it is turned off. Normal DC motors do have a low torque, therefore our choice fell on BLDC motors. We chose a gimbal BLDC motor that can provide a high torque with lower speed.

If we want to control a low speed but high torque BLDC motor, we need a position encoder that tracks the position of the motor coils to provide constant torque. Otherwise, the controller would not know where the coils are and would cause an undesirable cogging effect. The position encoder needs to track the coils fast enough for the user's movements. Therefore, a fast communication between encoder and microcontroller is necessary, where we chose the serial peripheral interface (SPI) communication.

After we found a suitable motor and encoder, the next important step was to use a suitable motor driver board that can control the motor with a constant torque. To do so, we used the field oriented control technique (FOC) [21]. Simply explained, FOC generates an optimal pushing effect on the motor's rotor, by calculating the phase voltage which creates the magnetic field that is exactly perpendicular to the magnetic field of the permanent magnets. We chose this technique, because it provides a precise torque control. In order to get the best torque control, we used inline current sensing, where we measure the current on two shunt resistors to regulate the current the motor receives. This approach causes an accurate torque control. We used the code of the open source library SimpleFOC [1]. The simple FOC algorithm with the inline current sensing method uses a PID controller to steer the torque of the motor. Therefore, the last step was to set the PID parameters in order that the motors torque behavior suits to our weight simulation. We set the parameters such that STROE reacts quickly to the users movement.

#### 4.3.2 Lift Object

We found that it does not feel realistic when we simulate the full weight of an object that is resting on a support, immediately after people lift it. If the object is heavy, it immediately pushes the user's hand down a few inches, which can result in a collision with the ground that stops the weight simulation. This behavior causes a cogging effect and feels unrealistic. When we look into the real physical lifting process, we see that users tense their muscles until the muscle strength outweighs the physical weight.

To simulate this behavior, we implemented a *weight increasing function* for the first centimeters of the lifting process. We increase the simulated weight in the first four centimeters from zero to the object weight. To do so, we tried different weight functions $f$ to investigate which one feels the most realistic, where $K$ is the offset with which we increase the force, in our case 4 cm. $x \in [0 < x < K]$ is the distance between the object's height and the start height, $M$ the current of the object that is proportional to its mass, $D$ the default current we defined to tighten the string, and $f$ the resulting current that has to be send to the motor. We tried the following:

- Linear: $f_L = \frac{M-D}{K}x + D$
- Quadratic: $f_Q = \frac{M-D}{K^2}x^2 + D$
- Sine: $f_S = sin(\frac{0.5\pi x}{K}) * (M-D) + D$

We empirically tested the functions ourselves. We tested the different functions multiple times with different object weights and immediately switched between the functions to reduce the time between distinguishing changes. We perceived the linear function as the most realistic one. With the sine function, we had a cogging effect with heavy objects as well and with the quadratic function, the weight sensation came with a short delay, which felt unrealistic.

#### 4.3.3 Design of Rod

We designed STROE's rod with a length of 50 cm. To calculate the length of the pole, we held a string horizontally in front of us with an outstretched arm. Where the string touched the ground, we measured the distance to the toes. Additionally, we mount the rod on the shoe oblique, to avoid collisions between the rod's end and the ground the user is walking on. We empirically tested different angles of the rod ourselves, to get the minimum angle that users can walk without colliding with the ground. With 40 degrees, we experienced good results. The rod is connected with the shoe by bearings. Because there is always a tension in the string between the pulley and the user's controller, the rod rotates automatically with the controllers movement without any mechanical actuation support. We decided against a rotational actuator to rotate the rod to keep STROE's design simple and reduce costs.

## 5 Technical Evaluation

In order to understand the technical limits of STROE, to know what weights it can simulate, and to further improve the technical aspects, we carried out a technical assessment. We measured the maximum force it can simulate, its latency, consistency, and the force during lifting and walking with a weight. To measure the generated force of STROE in different behaviors, we connected STROE's string to a load cell. We positioned the load cell straight above the second pulley in order to measure the force directed towards ground.

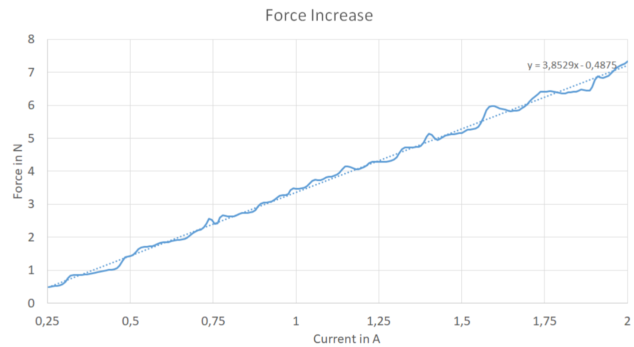


Figure 4: The measured force of STROE's motor with its corresponding current value. We chose 0.3 A as default current to tauten the string and increased the current to the motor's limit to 2 A.

**Maximum Force** To measure the maximum weight STROE can simulate, we increased the current to the motor linearly. To do so, the load cell is connected to the ground. Here, a force of 1 N means a weight simulation of 100 g. We began with 0.3 A that we chose as default force to strain the string and increase to 2.0 A, which is the motors current limit. Results can be seen in Figure 4. The default force was about 0.5 N and we measured the maximum force as 7.2 N. Compared to other haptic feedback devices we can produce more force than Windblaster [18] (1.5 N), and Thor's Hammer [14] (4 N), but less than Aero-Plane [17] (14 N). However, we can easily increase the maximum force by using stronger motors, without increasing the hearable noise level, in contrast to these other devices. Figure 4 also shows a current-dependent linear force increase that we use to calculate the current to simulate specific weights.

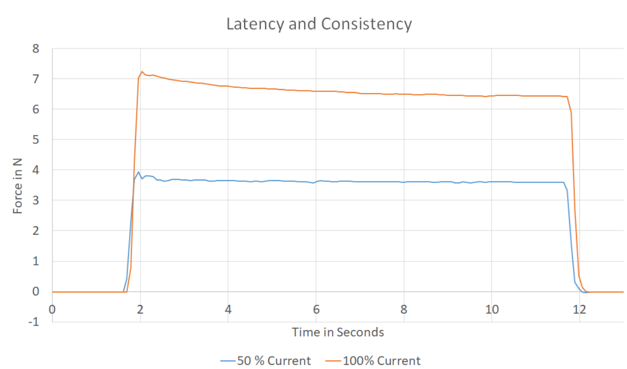


Figure 5: The measured latency and consistency over 10 seconds with 50% and 100% of the motor's maximum current.

**Latency and Consistency** We also measured the time STROE needs to produce a force (Latency Up) of 3.5 N (50 % current) and 7.0 N (100 % current) and back to the default force (Latency Down), see Figure 5. Additionally we measured how consistently STROE

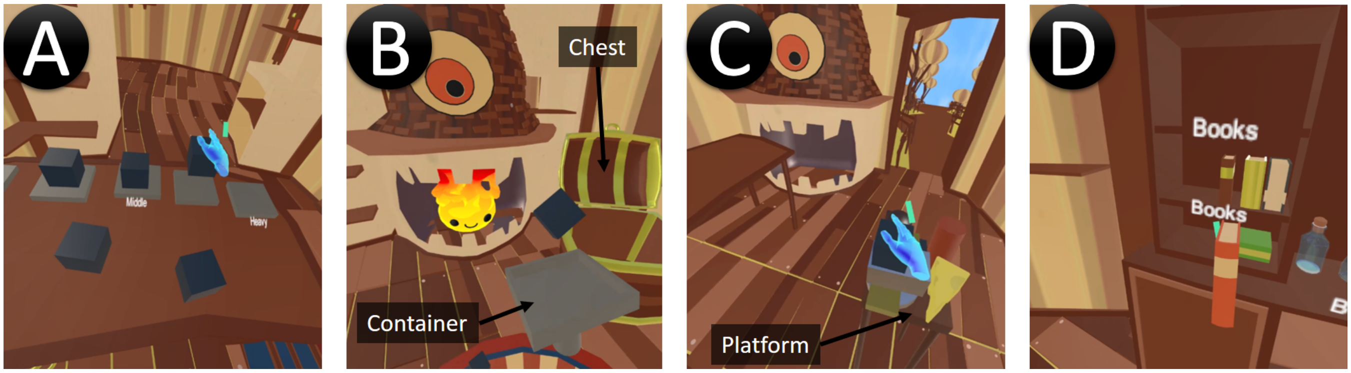


Figure 3: The four scenarios we implemented for our user study. (A) the Sort Objects scenario, (B) the Catch Objects scenario, (C) the Place Objects scenario and (D) the Tidy Up scenario.

| Current | Force | Latency Up | Latency Down | Cons. |
|---|---|---|---|---|
| 50 % | 3.5 N | 250 ms | 200 ms | 0.02 N |
| 100 % | 7.2 N | 250 ms | 250 ms | 0.2 N |

Table 1: The measured force, latency to reach the corresponding force (Latency Up), the latency from corresponding force to default force (Latency Down), and the force consistency over 10 seconds.

can hold the force over 10 seconds. Table 1 shows the results. In Figure 5, we can also see a small overshoot in the force generation when the current is 100%. This is caused by the PID parameters we set, as we wanted to have a small latency. However, this overshoot is not an issue because of how we lift objects that we described in Section 4.3.2. Here, the force is increasing depending on the speed of the user's lifting behavior. The user would have to lift the object very fast in order to feel the overshoot.

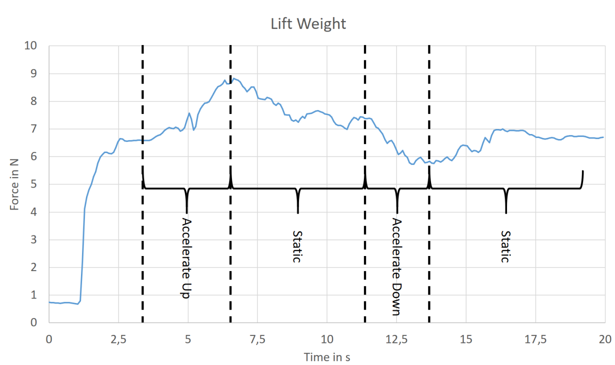


Figure 6: The measured force in one lifting process. The lifting process contains the following steps: Move the object up (Accelerate Up), hold one height with the object (Static), move the object down to the start height (Accelerate Down), and let the object go (static). Here, we can see that the inertia is also simulated by STROE.

**Lift Weight** In the real world, when users lift a weight and accelerate it, they perceive a force that is greater than the real weight of the object due to its inertia. We measured the force STROE exerted on the users while lifting a weight to see if we can simulate inertia. Figure 6 shows the result of lifting a simulated weight of 7N by STROE for 60 cm. The figure shows the effect of the inertia, that increase the weight during acceleration. When the user moves a weight in the opposite direction of the gravity vector, the force to move the weight is more than the original weight because of the inertia and vice versa. We can see this effect by looking at the measured data.

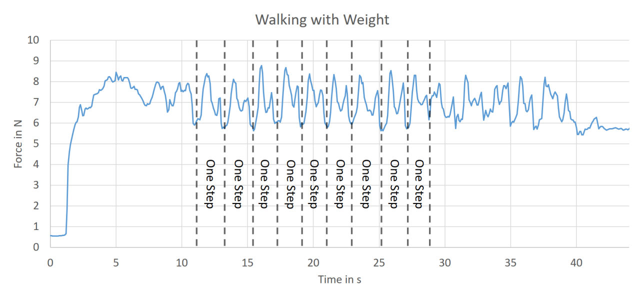


Figure 7: The measured force during walking multiple steps with a current of 2 A. Here we can see a repeating pattern for each step.

**Walking with Weight** STROE's design allows to simulate weight while walking. However, moving STROE during walking can affect the force the users receive. Therefore, it is important to produce a constant force while walking. We measured the force consistency while the user is moving multiple steps. While walking, the user holds a handle where the load cell is mounted on, while walking. The user tried to keep his hands steady. We measured the force for the walking direction forward, backward, right, and left. Figure 7 shows the result of one user walking forward while STROE produced a force of 7 N. We measured a deviation of 0.64 N while moving forward, 0.50 N backwards, 0.48 N right, and 0.51 N left. The step length was about 37.5 cm forward, 25 cm backward, and 32 cm for left and right steps. Additionally, we can recognize a pattern for each step, that can be used to decrease the deviation with signal processing in future work.

## 6 Study

We conducted a proof of concept study in order to evaluate the potential of STROE and its performance in different scenarios.

### 6.1 Scenarios

We have implemented four different VR scenarios in Unity, which we described below. In Unity, we assign a weight to every object that can be grabbed. If the user grabs one object, the *weight increasing function* is called and the resulting weight is sent via Bluetooth to STROE's Microcontroller. Here, the FOC algorithm generates the torque according to the weight it received.

We ordered the scenarios according to the how much participants have to walk in each scenario. From static scenarios to walk-intensive scenarios.

### 6.1.1 Sort Objects

In this scenario, the participants have to sort five cubes by their weight, see Figure 3 A. The cubes look the same but have different weights (180 g, 325 g, 440 g, 580 g and 730 g). We chose this scenario to investigate how well STROE can offer various weight simulations. In this scenario, participants usually do not move their feet. We measured how many cubes were sorted correctly and how long participants needed.

### 6.1.2 Catch Objects

Here, the participants had to catch objects with a small container and throw them into a chest, see Figure 3 B. We assigned this container a weight of 275 g and the objects they have to catch 200 g. Here, STROE simulates the weight of the container and the weight of a caught object while it lies in the container. This scenario requires quick upper body movements but is mostly stationary. Here, we evaluate whether STROE's string limits the fast movements and whether the delay is acceptable. We measured the number of dropped and caught objects and the time participants spent there.

### 6.1.3 Place Objects

In this scenario, participants need to place different blocks on a small platform without knocking the other items down, see Figure 3 C. The shape, size, and weight of the objects are different. We choose simple shapes such as cubes, cylinders, cones or pyramids. The weights of the objects were between 180 g and 730 g. The items are placed on tables next to the platform, so participants have to move around a lot while holding the items. We chose this scenario because we wanted to find out how well the participants can move while holding the objects and whether the weight of the objects influences their decision on where to place the objects on the platform. We measured how many items were accidentally dropped from the platform and the time they needed

### 6.1.4 Tidy Up

This scenario is about tidying up a room, see Figure 3 D. The participants have to grab objects on the desks and position them in the designated place. In this use case, the participants have to walk the most. The room they have to tidy up has an area of $3m \times 3.5m$. Here we measured the time they spent in this scenario.

## 6.2 Participants

We had 12 participants (10 male, 2 female) with an average age of 25.4 (SD: 3.7) years. 8 participants were experienced in VR, 4 were beginners or had not had contact with VR before. 5 participants had experience with haptic devices in VR. Additionally, 11 participants were interested in VR applications.

## 6.3 Procedure

Participants conducted the study under a VR rig and used the HTC Vive and its controllers. The VR rig is approximately $4m \times 4m$ in size and gives participants the opportunity to walk freely. We conducted a within-subject study with two conditions, the **visual-only** condition and the **visual-haptic** condition. For the visual-haptic condition, we attached STROE to the shoe on the side of the dominant hand and connected it to the corresponding controller. Only the Sort Object Scenario was done with just the visual-haptic condition, because the participants cannot solve the task without haptic feedback. The order of the conditions were randomized to avoid learning effects. The participants first explored a training scenario with STROE in order to get used to it. In the training scenario, they could freely walk in a virtual room and lift different objects.

Our main intention in this study is to measure the potential increase in realism and immersion, which is essential for our application domain. We did that using the respective questionnaires. To further enrich this data, we also measured **quantitative task performance** as described in the scenario descriptions. Note, that the quantitative task performance measures are not our main focus though. In fact, we expect that haptic feedback conditions will even lower the quantitative task performance measures, as tasks are becoming more realistic and as such harder to conduct. For instance, if the task is to assemble a car component, the heavier the car component is the more challenging the task, and therefore we would expect the task performance to decrease. This realism is essential for domain tasks such as automotive build-ability studies. The main purpose is to simulate in VR how hard these tasks are in reality; the goal is not to make the VR experience as easy and fast as possible.

After each condition, we gave the participants a questionnaire about the **user experience**. Here, they had to rate fun, realism, and immersion of the scenario on a 5-point Likert scale. After each scenario, we interviewed the participants and asked only about the **haptic experience**. Our questions were partially based on the questions from Kim et al. [19], which provide guidelines for building haptic feedback devices. We asked to rate consistency (Is it reliable?), sailency (Is it appropriately noticeable?), and harmony (Does it fit with the other senses?) on an 5-point Likert scale. In addition, we asked whether STROE restricts their movement and how realistic the weight feels when walking. At the end of the study, we collected additional qualitative feedback by asking **general questions** about which scenario they prefer and why, if they prefer with or without haptic feedback, whether they have suggestions for improvement and what they liked and did not like about STROE. We audiorecorded, transcribed, and coded these interview parts.

## 6.4 Results

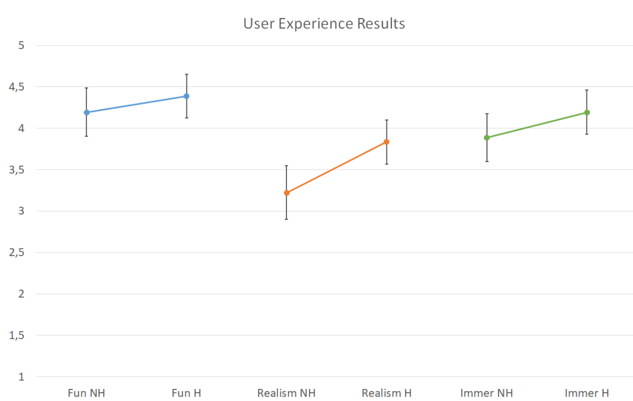


Figure 8: The results and their 95% confidence interval of the overall experience questions about fun, realism and immersion with none haptic feedback (NH) and with haptic feedback (H).

We split our results corresponding to the questions we asked. First, we report the overall experience to see which effect STROE has on the overall VR experience. Afterwards, we report the haptic experience to find out which aspects of the haptic feedback worked well and which not. At the end, we present qualitative feedback of the participants. Our results is based on an exploratory proof of concept study. Therefore, we used an estimation-based approach with effect sizes and confidence intervals to interpret our results. This approach is recommended by statistical analysis practices [6] and overcomes several limitations and biases of classical null hypothesis testing with p-values (NHST) [10, 12]. Cumming and Finch provide guidance on how p-values can be eye-balled from 95% CI plots [11].

### 6.4.1 User Experience

In the overall experience, we can see that on average the participants had more fun and perceived the VR scenarios with STROE more realistically and immersively, see Figure 8. The highest increase were in the realism from 3.2 without STROE to 3.8 with STROE. Afterwards, the immersion increased from 3.9 to 4.2 and the lowest increase was the fun experience from 4.2 to 4.4. In Figure 9 we can see the fun, realism, and immersion ratings per scenario. Here, we notice that perceived fun decreases with the scenario order, which we assume also depends on the amount the participants had to walk.

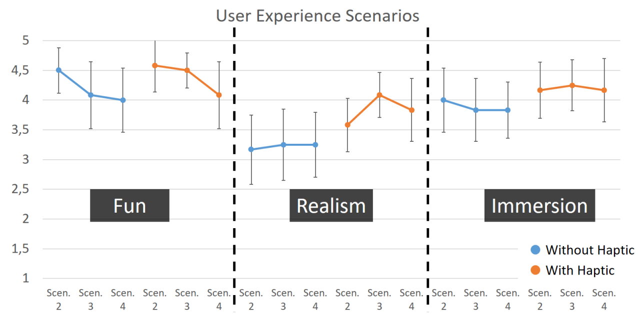


Figure 9: The results and their 95% confidence interval of the overall experience questions about fun, realism, and immersion for the second, third, and fourth scenario with and without haptic feedback.

### 6.4.2 Haptic Experience

Overall, we were satisfied with the results of the haptic experience question, which shows a potential in the technical aspects of STROE. Figure 10 shows the results of the questions of the 5-point Likert scale for each scenario.

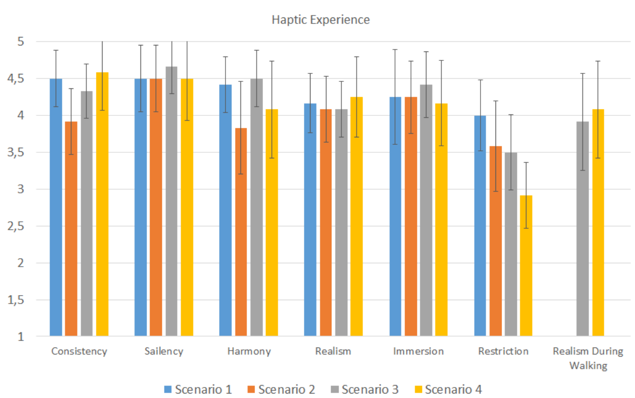


Figure 10: The results and their 95% confidence interval of the haptic experience questions for each scenario.

On average, the results about the consistency were 4.3 (SD: 0.78) which demonstrates the reliability of the technical design. The consistency was rated the lowest in the *Catch Objects* scenario, because 8 participants reported a judder in the feedback when the block was jumping on the container. This can be explained by the implemented collision behavior. Every time the block collided with the container, STROE simulates the weight of the block. When the block bounces on the container, STROE will trigger multiple force stimuli in a short time. Most of the participants perceived this behavior as too extreme. However, one participant described this behavior as very realistic. 4 participants criticized the consistency, because sometimes the force was not perceived fully downward, since they leaned their upper body too much to the front and STROE's rod was too short.

The sailency was rated 4.5 (SD: 0.8) on average and the harmony 4.2 (SD: 0.94) which showed us sufficient results. One participant mentioned, that they missed a weight shifting when the block jumped from one side of the container to another.

The realism was scored 4.2 (SD: 0.77) on average and the immersion 4.3 (SD: 0.94), which showed us that the idea to simulate weight with the motor attached on a shoe feels realistic. One participant told us in the *Catch Objects* scenario: "*So in comparison without haptic feedback, it was much, much more real, so it felt really real and even when I let [the block] go, it really felt like I was catching something with a container and throwing it away again, that was really good*". However, 5 participants reported that placing the objects on another object or platform feels unrealistic, because the weight simulation stops too immediately. Here, we have to use the same weight increase function that we implemented for the lift object that we explained in section 4.3.2. Another criticism about the realism, which was mentioned by 2 participants, was that the feedback is triggered on the controller and not directly on the user's hand.

On average, the restriction was rated the lowest with 3.5 (SD: 0.97) where 5 means no restriction in your movement and 1 means very high restriction. In Figure 10, we can see that the restriction ratings increase depending on the scenario. The participants felt less restricted when they had a more static scenario and more restricted if they had to walk a lot. Some participants described the restriction of walking due to STROE like wearing a "skier", "flipper", or "bandage". Additionally, 3 participants reported that their other foot collided agains STROE's rod, which irritated them a little. However, other participants told us they just had to used to it, one explained: "*If you have tested it for a while and you can see that it can withstand fast movements, then you can move with it without being restricted*".

We were surprised about the positive ratings on the felt realism during walking. We were not sure how much the connection between foot and hand will effect the perceived weight sensation during walking. One participant explained about the force sensation during walking: "*If you concentrate on your hand you don't notice any difference between walking and standing*". The participants rated the realism during walking with 4.0 (SD: 1.14) and reported that the perceived weight did not change during walking.

### 6.4.3 Quantitative Task Performance

In the *Sort Objects* scenario, we were positively surprised about the successful sorting results. Each participant correctly sorted all objects according to their weight. On average, they needed 80 seconds (SD: 17.5). In the *Catch Object* scenario, the participants without haptic feedback caught on average 59% (SD: 13%) of the objects and threw them in the chest and 43% (SD: 13%) with haptic feedback. On average, participants dropped 0.7 (SD 0.8) objects without haptic feedback in the *Place Objects* scenario and 1.9 (SD: 2.4) with STROE. They needed on average 101 seconds (SD 14) to complete the task without haptic feedback and 141 seconds (SD: 39) with haptic feedback. In the *Tidy Up* scenario, the participants needed on average 180 seconds (SD: 39) to complete the task without haptic feedback and 256 seconds (SD: 39) with haptic feedback. As expected the task performance got harder with haptic feedback, which we see in the increased time and error measures.

### 6.4.4 General Question

We were happy that 9 of 12 participants preferred their favorite scenario with STROE. 8 participants liked the *Catch Objects* scenario the most where 5 participants prefer the scenario with using STROE. 2 Participants preferred the *Tidy Up* scenario with haptic feedback and 2 participants preferred the *Place Objects* and *Sort Objects* scenario each, both with haptic feedback.

The suggestions for improvements were mostly about ergonomics and wearing comfort. The participants came up with the idea of placing STROE's heavy hardware components more centrally on the shoe in order to better balance the weight and enable better movement. In addition, they wished for a smaller and lighter design of STROE and a better mechanism to attach it tighter to the user's shoe. Some participants suggested to glue rubber onto STROE's sole in order to decrease the hearable noise that arises when the users make a step with the current plastic sole. One participant had the idea to insert a damper for the rod rotation to decrease the swing effect of the rod. Another idea was to increase the length of the rod to prevent forces that are not directed to the ground. One participant suggested to attach the string directly to the hand instead of the controller in order to get a more realistic weight sensation.

Regarding the question what they liked, some participants mentioned the arm freedom and the mobility. One participant said: "*That's the first step into mobility, it's very mobile compared to other things I know*". Other participants liked the increased realism. One participants told us: "*It just feels much more realistic. So in comparison to without [haptics], something is really missing if it is not included*". One participant explained us that he liked the idea to attach the hardware on the shoe, he said: "*I don't notice that the pulling that is causing the feedback on my hand is coming from my foot, I didn't even notice that. I think that was very good*".

Most of the participants agreed on what they did not like about STROE. They mentioned the movement restriction caused by the unergonomic design of STROE and the wearing comfort. None of the participants raised concerns about the technology STROE uses to exert forces on users.

## 7 Discussion

In the following, we discuss whether STROE meets the design requirements we collected from related work and our experience with VR engineers from the automotive industry. Additionally, we discuss the limitations of STROE.

### 7.1 Design Requirements

Based on our study results, we showed that the users can walk with STROE (**R-Mobility**). We were surprised about the positive feedback how realistic the weight sensation is during walking. Therefore, we belief that our design idea has potential for ungrounded weight simulation. However, they criticized the wearing comfort and the ergonomic behavior, which we are confident to improve with design adaptions. Our technical method to generate a force does not create switchhearable noise (**R-Quiet**). However, some participants were annoyed by the switchsound that was generated by the contact between STROE's plastic sole and the ground. The participants were able to put the shoe on in less than 30 seconds (**R-Simple**) and the only skin contact it has is with the controller, therefore we just had to clean the controller before giving STROE to the next user (**R-Hygiene**). In total, our hardware costs about 150 USD, whereby we are satisfied as our costs are comparable with a new HTC Vive controller that costs about 140 USD (**R-Price**). Regarding the latency (**R-Latency**), the participants did not notice any latency. Some participants told us that they liked the immediate force change when they throw an object away.

### 7.2 Design Improvements

Some participants reported, that they perceived a slight mechanical noise in the weight sensation, when they do fast and large arm movements. This is caused by the design of the rod's rotation. When a user moves their arm fast for a longer distance, the rod begins to rotate and there is an overshoot in the rotation when the user stops their arm immediately. To fix this problem, we can use a motor that controls the rotation of the rod. For that, we would recommend a brushless DC motor, with a high velocity.

The major problem the participants mentioned was the constrain in walking caused by STROE's design. To improve this behavior, we have multiple ideas, that we want to test in the next prototype. One idea is to round the shape of STROE's sole and to attach rubber material on it. The design would then allow the user's foot to roll and it would decrease the hearable noise. Additionally, we want to create a better weight distribution in the design. At the moment, most of the weight of STROE is in the front of the shoe, which causes problems during walking. We have two different ideas to solve this issue. First, we can place the battery, Arduino, and the driver board further back on the outer side of the shoe, to distribute the weight more equally. Second, we can attach the battery, Arduino, and the driver board on the user's calf and place the motor with the string on the side and back of the shoe, and connect the string with the movable pulley via additional rolls. Another idea that reduces the walking restriction is, to redesign the device to directly attach the rod to the user's shin instead of the foot. Thus, the users would have no restriction on their foot.

In the walking with weight section 5, we saw that the force magnitude depends on the direction of the users step. The study results showed that the participant did not notice a force variation during their walking. However, increasing the maximum force STROE can apply will increase the force magnitude variation and we assume participants will notice it when the force is strong enough. A next step is to track the step direction and use this information to control the force magnitude. For this purpose, we want to use the tracker's orientation that is attached on the user's foot.

### 7.3 Limitations

A limitation that arose is the ability of simulating the center of mass. With one string it is currently not possible to simulate any weight shift. However, there are already some devices that can simulate weight shift, such as Shifty [30]. In a next step, we want to combine both devices. Another limitation is the restriction of free walking. Our study shows that the users could walk during weight simulation but in a restricted way. One limitation that came up was the speed of the pulley that was controlled by the stepper motor. The stepper motor is good in holding one position even when external forces were applied. However, stepper motors are not as fast as brushless motors. In the next prototype, we therefore want to further control the pulley position with a brushless motor. Another limitation is the usage of two STROEs at the same time. When users cross their hands, the rods of the STROEs could collide with each other. Therefore, we want to include a mechanical stopper that stops the rods rotation in the case of using two STROEs. In addition, there are limitations in the current control system that can be improved to increase accuracy. For example, in the next prototype we want to use a tension sensor in the control system.

## 8 Conclusion and Future Work

We introduce STROE, a new ungrounded string-based haptic feedback device. STROE can be attached to the user's shoe for mobile usage. It consists of an motor with a string that is connected to the user's controller in order to simulate weight in VR applications. We conducted a user study with 12 participants. The main results show that STROE can simulate weight precisely and reliably even during walking. It increased the participants perceived fun, realism, and immersion in the VR scenarios. Although the participants could walk with STROE, they mentioned some optimization problems and limitations.

The most important aspect of STROE we have to improve is its wearing comfort and ergonomic design. We want to design STROE smaller and lighter with a better balance in its weight distribution. Additionally, we want to test STROE in an industrial environment within an expert study, to measure how suitable it is for industrial use cases such as buildability tasks in the automotive industry.


## Acknowledgments

Supported by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany´s Excellence Strategy – EXC 2120/1 – 390831618.

## References


[1] Arduino simple field oriented control (foc) library. https://github.com/simplefoc/Arduino-FOC.

[2] ipower motor gm3506 brushless gimbal motor. https://shop.iflight-rc.com/.

[3] Simplefocshield v2.0.3. https://simplefoc.com/simplefoc_shield_product_v2.

[4] P. Abtahi, B. Landry, J. Yang, M. Pavone, S. Follmer, and J. A. Landay. Beyond the force: Using quadcopters to appropriate objects and the environment for haptics in virtual reality. In *ACM Conference on Human Factors in Computing Systems (CHI)*, pp. 1–13, 2019.

[5] A. Achberger, F. Heyen, K. Vidackovic, and M. Sedlmair. Propellerhand: A hand-mounted, propeller-based force feedback device. In *ACM Conference on Visual Information Communication and Interaction (VINCI)*, 2021. doi: 10.1145/3481549.3481563

[6] A. P. Association. Publication manual of the american psychological association (6th edition). *American Psychological Association Washington*, 2010.

[7] C. Bonivento, A. Eusebi, C. Melchiorri, M. Montanari, and G. Vassura. Wireman: A portable wire manipulator for touch-rendering of bas-relief virtual surfaces. In *IEEE Conference on Advanced Robotics (ICAR)*, pp. 13–18, 1997.

[8] C.-H. Cheng, C.-C. Chang, Y.-H. Chen, Y.-L. Lin, J.-Y. Huang, P.-H. Han, J.-C. Ko, and L.-C. Lee. Gravitycup: a liquid-based haptics for simulating dynamic weight in virtual reality. In *ACM Symposium on Virtual Reality Software and Technology (VRST)*, pp. 1–2, 2018.

[9] I. Choi, H. Culbertson, M. R. Miller, A. Olwal, and S. Follmer. Grabity: A wearable haptic interface for simulating weight and grasping in virtual reality. In *ACM Symposium on User Interface Software and Technology (UIST)*, pp. 119–130, 2017.

[10] G. Cumming. *Understanding the new statistics: Effect sizes, confidence intervals, and meta-analysis*. Routledge, 2013.

[11] G. Cumming and S. Finch. Inference by eye: confidence intervals and how to read pictures of data. *American psychologist*, 60(2):170, 2005.

[12] P. Dragicevic. Fair statistical communication in hci. In *Modern statistical methods for HCI*, pp. 291–330. Springer, 2016.

[13] P. Garrec, J.-P. Friconneau, and F. Louveau. Virtuose 6d: A new force-control master arm using innovative ball-screw actuators. In *Symposium on Robotics (OSR)*, 2004.

[14] S. Heo, C. Chung, G. Lee, and D. Wigdor. Thor's hammer: An ungrounded force feedback device utilizing propeller-induced propulsive force. In *ACM Conference on Human Factors in Computing Systems (CHI)*, pp. 1–11, 2018.

[15] Y. Hirata and M. Sato. 3-dimensional interface device for virtual work space. In *IEEE/RSJ Conference on Intelligent Robots and Systems (IROS)*, pp. 889–896, 1992.

[16] M. Hirose, K. Hirota, T. Ogi, H. Yano, N. Kakehi, M. Saito, and M. Nakashige. Hapticgear: the development of a wearable force display system for immersive projection displays. In *IEEE Virtual Reality (VR)*, pp. 123–129, 2001.

[17] S. Je, M. J. Kim, W. Lee, B. Lee, X.-D. Yang, P. Lopes, and A. Bianchi. Aero-plane: A handheld force-feedback device that renders weight motion illusion on a virtual 2d plane. In *ACM Symposium on User Interface Software and Technology (UIST)*, pp. 763–775, 2019.

[18] S. Je, H. Lee, M. J. Kim, and A. Bianchi. Wind-blaster: A wearable propeller-based prototype that provides ungrounded force-feedback. In *ACM SIGGRAPH Emerging Technologies*, pp. 1–2. 2018.

[19] E. Kim and O. Schneider. Defining haptic experience: Foundations for understanding, communicating, and evaluating hx. In *ACM Conference on Human Factors in Computing Systems (CHI)*, pp. 1–13, 2020.

[20] Y. Kuniyasu, S. Fukushima, M. Furukawa, and H. Kajimoto. Weight illusion by tangential deformation of forearm skin. In *ACM Conference on Augmented Human International Conference (AH)*, pp. 1–2, 2011.

[21] H. Le-Huy. Comparison of field-oriented control and direct torque control for induction motor drives. In *IEEE Conference on Industry Applications*, vol. 2, pp. 1245–1252, 1999.

[22] P. Lopes, S. You, L.-P. Cheng, S. Marwecki, and P. Baudisch. Providing haptics to walls & heavy objects in virtual reality by means of electrical muscle stimulation. In *ACM Conference on Human Factors in Computing Systems (CHI)*, pp. 1471–1482, 2017.

[23] C. Melchiorri, G. Vassura, and P. Arcara. What kind of haptic perception can we get with a one-wire interface? In *IEEE Conference on Robotics and Automation (ICRA)*, vol. 2, pp. 1620–1625, 1999.

[24] K. Minamizawa, S. Fukamachi, H. Kajimoto, N. Kawakami, and S. Tachi. Gravity grabber: wearable haptic display to present virtual mass sensation. In *ACM SIGGRAPH Emerging Technologies*, pp. 8–es. 2007.

[25] K. Nagai, S. Tanoue, K. Akahane, and M. Sato. Wearable 6-dof wrist haptic device" spidar-w". In *SIGGRAPH Asia Haptic Media And Contents Design*, pp. 1–2. 2015.

[26] R. Niiyama, L. Yao, and H. Ishii. Weight and volume changing device with liquid metal transfer. In *ACM Conference on Tangible, Embedded and Embodied Interaction (TEI)*, pp. 49–52, 2014.

[27] J. Perret and L. Dominjon. The inca 6d: A commercial stringed haptic system suitable for industrial applications. In *Joint Virtual Reality Conference, Springer Tracts in Advanced Robotics*, 2009.

[28] M. Samad, E. Gatti, A. Hermes, H. Benko, and C. Parise. Pseudo-haptic weight: Changing the perceived weight of virtual objects by manipulating control-display ratio. In *ACM Conference on Human Factors in Computing Systems (CHI)*, pp. 1–13, 2019.

[29] J. Shigeyama, T. Hashimoto, S. Yoshida, T. Aoki, T. Narumi, T. Tanikawa, and M. Hirose. Transcalibur: weight moving vr controller for dynamic rendering of 2d shape using haptic shape illusion. In *ACM SIGGRAPH Emerging Technologies*, pp. 1–2. 2018.

[30] A. Zenner and A. Krüger. Shifty: A weight-shifting dynamic passive haptic proxy to enhance object perception in virtual reality. *IEEE Transactions on Visualization and Computer Graphics (TVCG)*, 23(4):1285–1294, 2017.