Providing Haptics to Walls & Heavy Objects in Virtual Reality by Means of Electrical Muscle Stimulation

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ABSTRACT
We explore how to add haptics to walls and other heavy objects in virtual reality. When a user tries to push such an object, our system actuates the user's shoulder, arm, and wrist muscles by means of electrical muscle stimulation, creating a counter force that pulls the user's arm backwards. Our device accomplishes this in a wearable form factor.

In our first user study, participants wearing a head-mounted display interacted with objects provided with different types of EMS effects. The *repulsion* design (visualized as an electrical field) and the *soft* design (visualized as a magnetic field) received high scores on "prevented me from passing through" as well as "realistic."

In a second study, we demonstrate the effectiveness of our approach by letting participants explore a virtual world in which all objects provide haptic EMS effects, including walls, gates, sliders, boxes, and projectiles.

Author Keywords
Muscle interfaces; virtual reality; EMS; force feedback.

ACM Classification Keywords
H5.2 [Information interfaces and presentation]: User Interfaces. - Graphical user interfaces.

INTRODUCTION
Recent virtual reality systems allow users to walk freely in the virtual world (aka *real walking* [36]). As the next step towards realism and immersion, many researchers argue that these systems should also support the haptic sense in order to convey the physicality of the virtual world [3,4].

There has been a good amount of progress towards simulating the haptic qualities of *lightweight* objects, such as contact with surfaces [17] or textures [8]. Solutions generally revolve around simulating the tactile qualities of the object, i.e., how the object affects the receptors in the user's skin. These include inflatable pads at the user's fingertips [20], vibro-tactile gloves [5], and glove exoskeletons [17].

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Unfortunately, adding haptics to *heavy* objects, such as furniture or walls, has proven substantially more challenging. Even if one simulates the tactile aspects of such objects, the illusion fails as soon as users try to *push* through the object, as their proprioceptive system informs them about the lack of resistance [28].

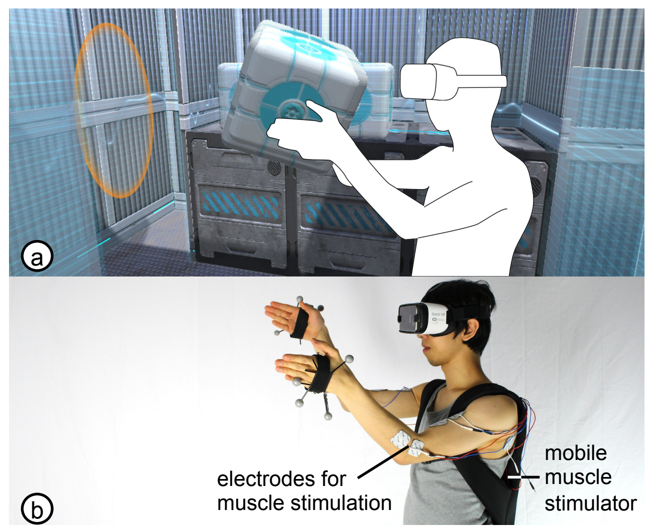

Figure 1: (a) As this user lifts a virtual cube, our system lets the user feel the weight and resistance of the cube. (b) Our system implements this by actuating the user's *opposing* muscles using electrical muscle stimulation.

Traditional approaches to simulating such objects in VR include the use of physical props [15], but even if one reuses props (by means of redirected walking [18] or human actuation [7]) the biggest limitation of this approach remains the size and weight of the props. The other traditional approach is to tether the user's hands (*SPIDAR* [25]). As a first step towards providing such forces to a non-stationary user, Nagai et al. proposed mounting a SPIDAR device into a ~1.5 x1.5 x 1.5 m cage that users carry around (*SPIDAR-W* [26]).

In this paper, we explore how to render heavy objects in VR in a truly wearable form factor.

ELECTRICAL MUSCLE STIMULATION HAPTICS FOR VR
Our main idea is to prevent the user's hands from penetrating virtual objects by means of electrical muscle stimulation (EMS). Figure 1a shows an example. As the shown user lifts a virtual cube, our system lets the user feel the weight and resistance of the cube. The heavier the cube and

the harder the user presses the cube, the stronger a counter-force the system generates. Figure 1b illustrates how our system implements the physicality of the cube, i.e., by actuating the user's *opposing* muscles with EMS.

Figure 2 illustrates the idea in more detail. (a) When the user grabs the virtual cube, the user expects the cube's weight to create tension in the user's *biceps* and the cube's stiffness to create a tension in the user's *pectoralis*. (b) In order to create this sensation, the system actuates the respective *opposition* muscles. In order to put a load onto the user's biceps, it actuates the *triceps* and in order to put a load onto the user's *pectoralis*, it actuates the user's *shoulder muscle*. This creates the desired tension in biceps and pectoralis, thereby creating the desired experience.

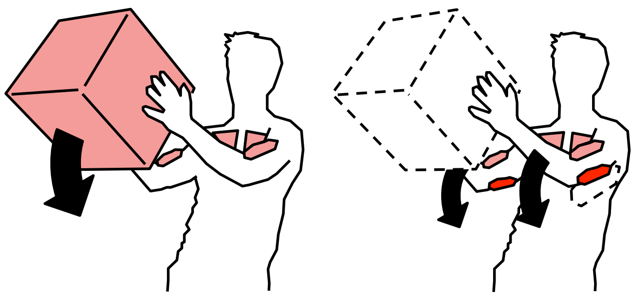

Figure 2: (a) When a user picks up a physical cube, its weight causes tension in the user's biceps. (b) Our system creates this tension by instead actuating the opposing muscles, here the user's triceps and shoulders.

As illustrated by Figure 3, our system stimulates up to four different muscle groups. Through combinations of these muscle groups, our system simulates a range of effects. When pushing a button mounted to a vertical surface, for example, the system actuates biceps and wrist. In the *Example Widgets* section we detail how this allows our system to simulate a wide range of objects, including walls, shelves, buttons, projectiles, etc.

Our system can be worn in a small backpack, as shown in Figure 3. The backpack contains a medical compliant 8-channel muscle stimulator (see also Figure 22 in the Implementation section), which we control via USB from within our VR simulators. We use our system in the context of a typical VR system consisting of a head-worn display (using a Samsung/Oculus GearVR) and a motion capture system (based on eight OptiTrack 17W cameras).

DESIGN

Based on this general concept of using EMS to bring force feedback to VR we can now design the user's experience. Two dimensions have substantial impact on the experience: (1) The intensity pattern we use to actuate the user's muscles and (2) the visuals and sound we present during this haptic event. It turns out that both of these are crucial in that they determine what physical event users will associate with the haptic sensation. These are also crucial for making the experience convincing.

Ideally, a design should fulfill four criteria, presented in order of decreasing importance: (1) *believable:* allow users to buy into the idea of the virtual object causing the experience, (2) *impermeable*: prevent users from passing through the object, (3) *consistent*: visual and haptic sensation should match, and (4) *familiar*: the experience should ideally resemble objects from the real world.

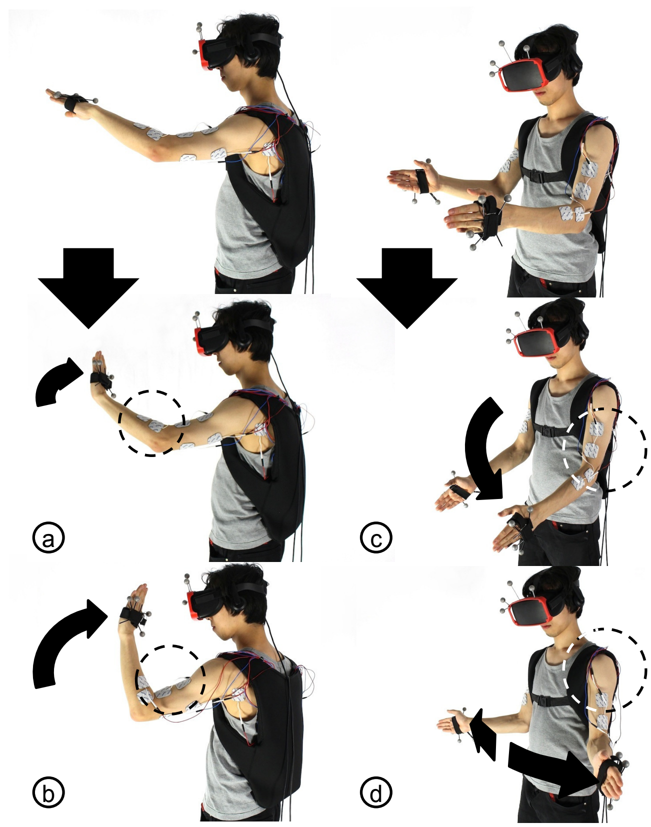

Figure 3: We use up to 8 electrode pairs, actuating (a) wrist, (b) biceps, (c) triceps, and (d) shoulders.

1. The hard object design does not work

Figure 4 illustrates the naïve approach to rendering objects using EMS: (a) From the moment the user's fingertips reach the virtual wall, we actuate the user's hand just strongly enough to prevent it from passing through. We achieve this with a current essentially proportional to the user's force (further details in Implementation).

When we built this version, the results *looked* great. The design prevents the user's hand from passing through the object and thus bystanders observing the scene would typically conclude that the illusion was "working".

However, during piloting it became clear that this design did *not* work. Since the EMS actuation was as long and as strong as the user kept pushing, the EMS signal (a tingling in the respective muscles) could become arbitrarily strong. This would draw the user's attention to the EMS-actuated muscles. These, however, were pointed in the wrong direction, i.e., they were pulling, when the sensation was supposed to be about pushing. One participant in our pilot said this design felt "like a magnet pulling the hand backwards".

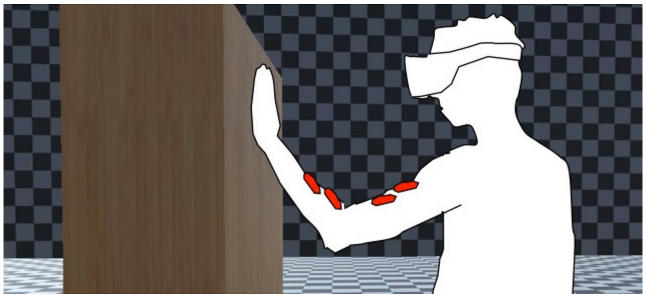

Figure 4: Implementing rigid walls requires stimulating muscles with strong impulses over long periods. This draws undesired attention to the electrical stimulation.

While this design was reasonably *impermeable*, *consistent,* and definitely *familiar*, the strong EMS signal made this design fail with respect to our primary objective: it was not *believable*.

We therefore created two alternative designs with the objective of increasing *believability*. In order to avoid the *long and strong* EMS signal that had made our actuation obvious, we created one design based on a *weaker* signal and one design based on a *shorter* signal.

2. The soft object design

We created our first alternative design by applying a cut-off to EMS intensity. We picked a reasonably low cut-off, allowing users to penetrate objects by about 10 cm. This resulted in a design that produced the impression of *soft* objects.

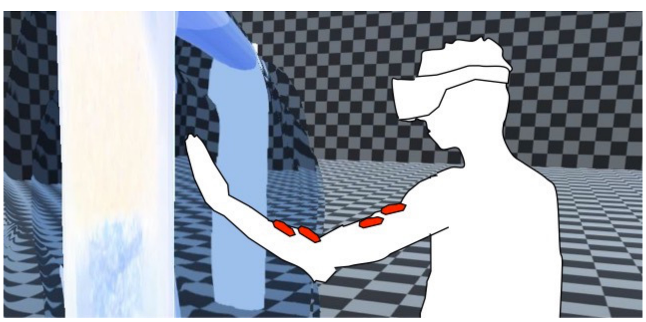

Figure 5: The *magnetic* visuals allow the user's hand to penetrate the surfaces of objects.

Based on this general concept, we explored various visuals, including the soft surface material shown in Figure 1, which is designed to suggest an increasingly solid inside under a soft, permeable surface. This general design became the basis for most of our object designs.

Figure 5 shows the same concept wrapped in visuals suggesting a *magnetic field*, suggesting a magnetic force that carefully pushes the user's hand backwards. In some versions of this design, we attached a block of metal to the back of users' hands to suggest that the magnetic field would apply there in order to affect the hand.

3. The repulsion object design

We created our second alternative design by reducing the *duration* of our EMS signal. This resulted in what we call *repulsion* objects. This design uses a brief EMS pulse (of 200-300 ms, using the user's calibrated maximum intensity) where the EMS propels the user's hand backwards, removing it from the virtual object it is trying to touch. We achieve this with an EMS pulse of still reasonably low intensity, which, like all other EMS signals in our system, is pain free at all times (for EMS pulses of similar intensity see *Impacto* [23]).

Again, we explored various visuals with this haptic design in order to help users rationalize what happens when they touch the object. Figure 6 shows what we call *electro* visuals. This design complements the EMS pulse with a strong white flash which turns the screen white for 100 ms and then fades it back in in 100 ms. At the same time, users hear a loud electrical "bang". To reinforce the effect further, we artificially enlarge the visual appearance of the user's hand movement, making it appear as if it was thrust backwards even further. In some cases, we complemented our EMS pulse with a strong vibration motor mounted to back of users' hands (an eccentric 5V DC motor operated at 12 volts) to suggest an electric flash hitting the user's hand.

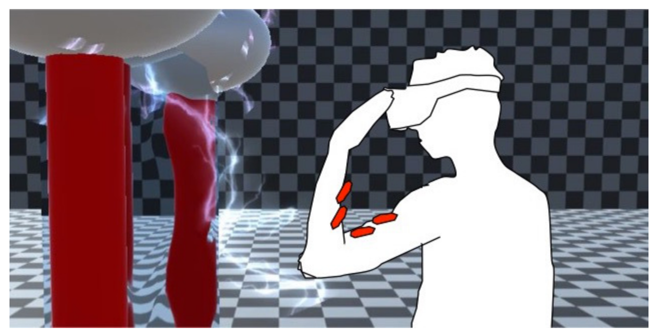

Figure 6: The *electro* visuals.

This gave us two functional designs, i.e., one to represent soft surfaces, as well as the repulsion design, which we would later use as a stand-in for hard surfaces.

FIRST USER STUDY—VALIDATING DESIGNS

We conducted a user study in order to (1) validate our core idea of using EMS as a means for adding haptics to heavy objects in virtual reality and (2) to validate the qualities of our *soft* and our *repulsion* object design. We immersed participants in a simple virtual world that contained nothing but five walls, each featuring a different haptic design. Participants touched all five of them and rated their qualities. We hypothesized that the *soft* and the *repulsion* design would perform best.

Interface conditions

Figure 7 shows the five "walls" arranged in a pentagon with the participant inside.

Each "wall" implemented one of five interface conditions:

1. The *soft* wall used the *magnetic* visuals from Figure 5.

2. The *repulsion* wall used the *electro* visuals (Figure 6).

We also included three additional conditions featuring more conventional visual explanations of a "hard" wall, all of which employed the visuals of a solid wooden wall as depicted in Figure 4.

3. The *soft wood* wall was identical to the *soft* wall, in terms of the EMS feedback, yet depicted a solid wooden wall. We used this condition to validate whether the visual design of the *soft* wall would add to the experience.

4. The *soft vibro wood* wall was identical to the *soft wood* wall, but also actuated the vibrotactile actuator on the back of participants' wrists. We used this condition to test whether vibro tactile would add to the experience.

5. The *vibro only* wall, finally, actuated *only* the vibrotactile actuator on the back of participants' wrists, but did *not* provide any EMS feedback. This condition served as baseline, as vibrotactile is the most common conventional approach to rendering haptic feedback in virtual reality (see our related work section).

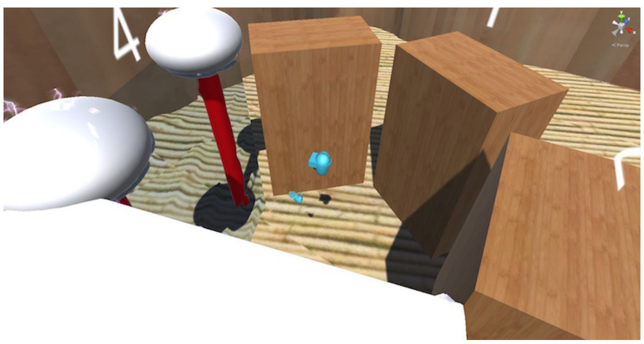

Figure 7: Study participant in the virtual world of the study, here facing the *vibro only* condition.

Apparatus
The apparatus was the prototype described earlier and shown in Figure 22. Participants wore EMS and vibrotactile actuators, one or both of which would be activated according to interface condition.

To reduce setup time, we actuated only *one* of the participants' hands. Also, since the set-up offered only vertical surfaces, we further simplified the set-up and used only two pairs of electrodes: one pair on participants' biceps and another pair on their wrist extensor muscle.

Task and procedure
Participants were prepared and placed into the virtual world shown in Figure 7. For each of five trials, the experimenter instructed the participant, which of the five walls to explore. Walls were labeled with numbers for that purpose. After touching the respective wall design for about 30 seconds, allowing for between 5 to over 20 touches, participants verbally rated this wall, which the experimenter wrote down. The order of the five interface conditions was randomized for all users prior to the start of the study.

Participants
We recruited 13 participants (4 female, 22.4 ±2.1 years). Six participants had previous experience with VR headsets and 5 had previously experienced EMS. With consent of the participants we videotaped the study sessions.

Hypotheses
Our hypotheses revolved primarily around the *repulsion* wall, the *soft* wall, and the *vibro only* baseline. (**H1**) The *repulsion* condition would be perceived as more realistic than the *vibro only* condition. (**H2**) The *soft* condition would be perceived as more realistic than the *vibro only* condition. (**H3**) The *soft* condition would be rated more realistic than the *soft wood* condition. (**H4**) The repulsion condition would be considered more impermeable than the *vibro only* condition.

Results
This section quotes Bonferroni-adjusted *p*-values.

Preference Eleven participants stated a preference for one of the EMS-based interfaces; only to two participants preferred *vibro only*. As depicted in Figure 8, eight participants picked the *repulsion* wall as their favorite. Another three listed this interface as their second favorite.

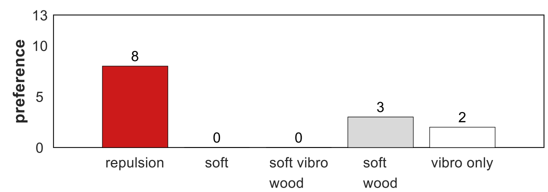

Figure 8: Eight participants picked the *repulsion* wall as their favorite design.

This suggests that our *repulsion* wall was particularly well designed. This raises the question what aspect of the repulsion design caused this preference. One explanation might be found in participants' assessment of the realism of this design.

Realism/consistency. Figure 9 shows how participants rated the five conditions with respect to the question "what I feel matches what I see." A repeated measures ANOVA (as suggested by [27]) found differences between conditions ($F(4,48) = 6.22$, $p = .000$).

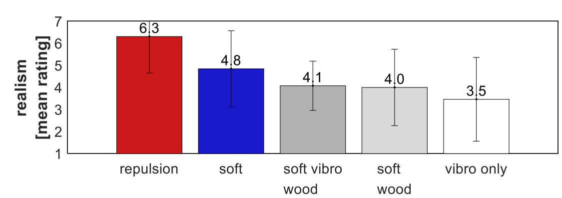

Figure 9: Participants rated the *repulsion* wall the most realistic and the *vibro only* the least realistic.

As expected, the repulsion condition received higher ratings than all other conditions, significantly so for *soft vibro wood* ($t(12) = -5.06$, $p = .002$) and *vibro only* ($t(12) = 3.71$,

p = .030) and with a strong trend with regard to *soft wood* ($t(12)$ = -3.38, p = .055). This confirms our hypothesis **H1.**

While the *soft wood* condition was rated higher than the *vibro only* condition, this difference was not found to be statistically significant. Hence, **H2** was not supported**.**

Even though there certainly was a trend, the differences between the *soft* condition and the three conditions that visually display a wooden texture were not found to be statistically significant. We thus found no support for hypotheses **H2** and **H3**.

The second possible explanation for participants' preference for the *repulsion* wall might be found in this design's performance.

Impermeability. Figure 10 shows participants' assessment of "this wall was able to prevent me from passing through". A repeated measures ANOVA found significant differences between conditions ($F(4,48)$ = 6.68, p = .000). The main finding here is that *repulsion* was rated as more impermeable than *vibro only* ($t(12)$ = 4.18, p = .013), which confirms our hypothesis **H4**.

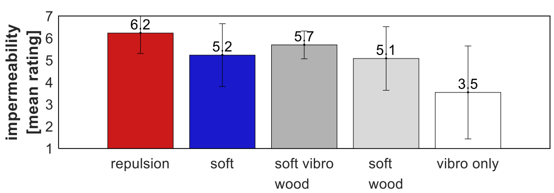

Figure 10: Participants rated any of the EMS conditions more impermeable than *vibro only*.

These responses are backed by our measurements on how deeply participants penetrated into each wall (Figure 11, measured using our optical tracking system *Optitrack 17w*).

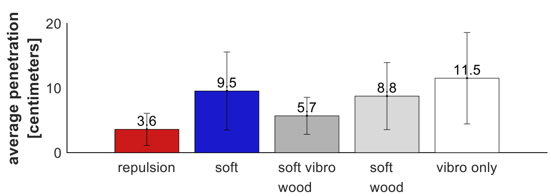

Figure 11: The *repulsion* wall stopped participants' hands on average 3.6 cm (error bars denote std. dev.).

A repeated measures ANOVA found a significant difference between conditions (F(4, 48) = 7.72, p = .000). The *repulsion* wall stopped participants' hands at only 3.6 cm on average, which is significantly earlier than *vibro only,* as a post-hoc t-test revealed ($t(12)$ = -3.54, p = .040). This provides additional support for our hypothesis **H4**.

Participants penetrate the *soft* wall significantly deeper than the *repulsion* wall ($t(12)$ = 3.69, p = .031). This, however, is expected, given that it had been designed to allow for 10 cm penetration.

Data of the average penetration in the virtual barriers was normal according to Shapiro-Wilk tests. The assumption of sphericity was not violated ($\chi 2(9)$ = 14.42, p = .11).

Participants commentaries and open-ended questions

All participants stated that the EMS was fitting the expectation of the "electro wall" visuals and noted its effectiveness in stopping them. P8 added "the pushing effect from these (virtual walls) felt like how a real wall pushes back". Another participant, P1, added, "EMS matched the springiness I expected of the wobbly wall". P5 remarked "it is funny because I feel (the wall's force) it but I know nothing is there".

One participant (P2) emphasized that the "EMS tingles and hence reveals the source of the force", yet, P7 stated "I did not realize how my hand was moving, I could not tell it was the EMS". Furthermore, three participants emphasized that the vibration did not match the expectations of the wooden walls.

Discussion

Our first study confirmed several key hypotheses. First, and maybe most important, it found that *any* of the EMS-based designs performs better than the most commonly chosen haptics option today: vibrotactile feedback.

The *repulsion* design did particularly well. It was rated the most *impermeable*, suggesting that it is suitable wherever virtual world designers have to stop users from passing through. This also recommends the *repulsion* design as a potential stand-in for rigid objects. The *repulsion* design also scored highest in terms of consistency between visuals and haptics. This matches our observation—the optical and acoustic effects behind this design work particularly well at covering up the EMS actuation, especially given that it is brief. Finally, and arguably most important, the majority of participants picked repulsion as their favorite design.

The *soft* design, while clearly not as strong as the repulsive design, demonstrated good "all-round" qualities. Reasonably realistic and reasonably impermeable it clearly outperformed vibrotactile. The combination with vibrotactile does not seem to lower performance, but does not add much either. It therefore seems reasonable to leave vibration out in the future and proceed with the *soft* actuation alone.

BENEFITS AND CONTRIBUTION

Our main contribution is the concept of providing haptics to walls and other heavy objects by means of electrical muscle stimulation. We achieve this in a wearable device, suitable for real-walking virtual reality environments.

Limitations include that users need to wear EMS equipment and that the design space works best for soft and repulsive objects, rather than truly rigid objects. Furthermore, we designed our haptic effects based on eight muscles from both shoulders and arms. These eight muscles alone were sufficient to create our plethora of haptic VR objects and obstacles. While adding more channels would possibly result in more complex haptic effects, it would also require attaching more electrodes and EMS hardware.

EXAMPLE WIDGETS

The *soft* design and the *repulsion* design together allow us to create the haptics for a reasonably wide gamut of virtual objects. In order to illustrate this, we have created a set of example objects and widgets. We combined these widgets into a simple virtual world, which forms the basis for our second user study (see below).

We use the *soft* design for the majority of objects. This design allows users to make physical contact with the object, as the user's hands partially penetrate into the object's interior. This helps maintain physical contact with an object, making it possible drag or carry objects around.

We use the *repulsion* design to complement the soft design and in particular, we use it to implement those walls, doors, and windows that are designed to prevent users from passing through, such as in a jail-like surrounding.

We continued to use electro visuals for the repulsion design. For the soft design we used a multi-layered translucent texture. In order to allow us to apply these designs to arbitrary objects, we implemented their visuals in the form of translucent textures.

We now demonstrate these widgets by giving a walkthrough of the simple virtual experience we designed for the second study. This VR experience consists of three rooms connected by three hallways. Inside this world, everything users can reach is complemented with a haptic effect based on one of the two designs, or based on an interpolation between the two.

Room 1: Repulsion.

We designed the first room so as to primarily illustrate the repulsion design.

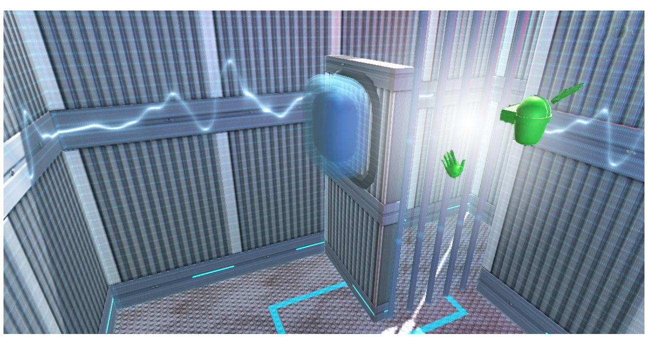

Figure 12: The jail cell features "electrified" walls and a gate. Touching any of these repel the user's hand.

Repulsion walls: As illustrated by Figure 12, this room is designed as a jail cell with an "electrified" gate and walls. When touched, these repel the user's hand, which is accompanied by the sound and visuals discussed earlier.

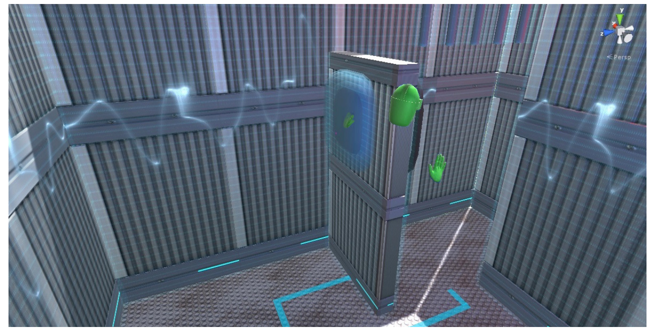

Figure 13: Pushing this soft button opens the gate.

Button: Figure 13: A button allows users to raise the gate. The button is soft, allowing the user's hand to penetrate its surface. The system accompanies this with a sense of increasing counter pressure. The button then tracks with the user's hand and the counter force stays constant until the button is all the way "in", at which point the counter force increases substantially.

Projectiles: As users rush down the hallway, a security system shoots projectiles at them, which they fend up with their hands. The system renders the 12" projectiles using a strong repulsion effect.

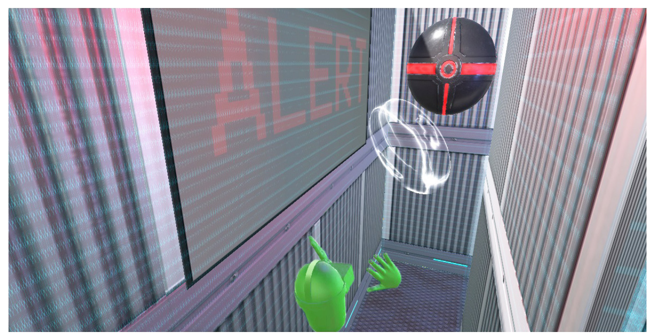

Figure 14: Projectiles based on the *repulsion* effect.

Room 2: Selected widgets

We use this room to illustrate some traditional GUI widgets rendered as interface elements in VR, in particular a slider and an analog rocker switch.

Slider mechanism: As shown in Figure 15, users operate a pair of traditional sliders in order to align the pipeline elements that establish a hydraulic link. The sliders' knobs are based on the soft design. The knobs protrude far enough to allow operation from multiple angles. If users operate the sliders while *facing* the wall, the system primarily actuates their shoulder muscles; if they turn *parallel* to the wall, the system interpolates from shoulder muscle to biceps.

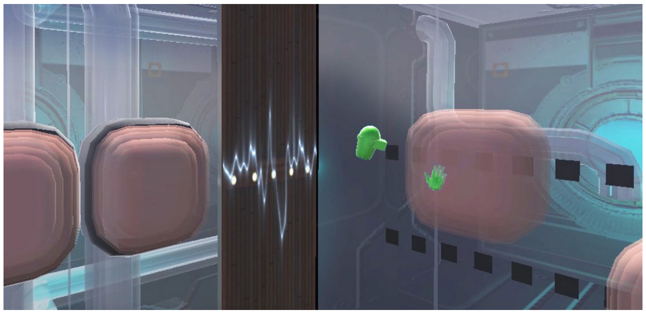

Figure 15: The user is dragging the knob of a slider mechanism. The two buttons on the left form a rocker.

Widgets that push back: Users can now operate the pump to re-establish pressure in the hydraulic system (Figure 15). The device consists of two buttons connected by a rocker mechanism, i.e., as users push one of the buttons in, the button comes out and pushes against their other hand, providing a simple animated haptic response.

Liquids: If users reach into the fish tank shown in Figure 16, their hand is pushed backwards by the water's viscosity. The system renders this by actuating the user's wrist.

Figure 16: Playing with the water in these fish tanks pushes the user's hand backwards.

Room 3: Lifting, punching, and throwing
We use this room to illustrate moveable objects.

Pushing, lifting, and dropping objects: As shown in Figure 17, there are two cubes. As users push the first one towards the adjacent button, they feel haptic feedback. Depending on the angle of attack, the haptic feedback actuates users' biceps, shoulder, or both.

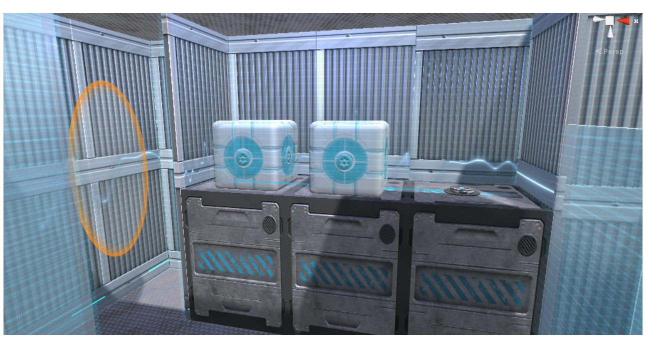

Figure 17: Two cubes that users can push onto the button on the right, or pick up and carry around.

If users *pick up* a cube with both hands (Figure 18), they feel a resistance when their hands come together as to grasp the cube. This happens because their shoulder muscles are stimulated as to open their arms outwards.

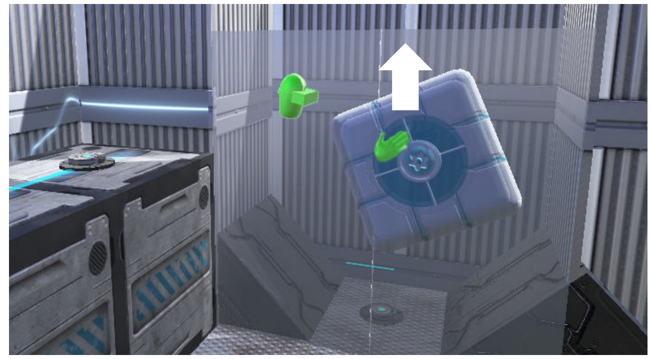

Figure 18: The user has picked up a cube and is about to throw it over the glass barrier.

Furthermore, users also feel the weight of the cube in their triceps, as discussed in the introduction. In Figure 18, we see how users pick up the cube and throw it over a glass wall, down a chute, which activates a second button.

Punching objects: Figure 19 shows a third cube that rests on a slide, which leads up to the last of the three buttons. If users push this cube they feel a soft effect in response. However, the contraption requires users to *punch* the cube up the slide in one go. The harder they hit the membrane, the more the system shifts its haptic response from *soft* effect to *repulsion* effect.

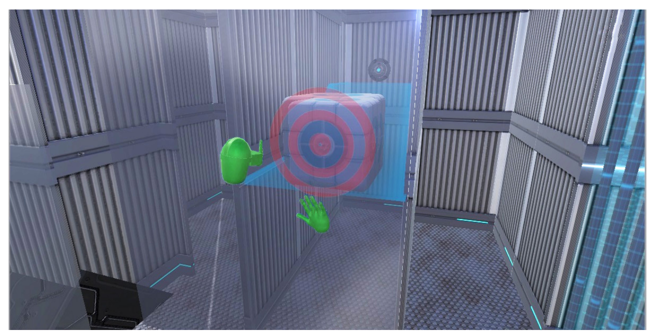

Figure 19: Users have to drive this cube up the ramp by punching it. The system responds with a mix between a soft effect and a repulsion effect.

USER STUDY 2: THE EXPERIENCE
Given that our first study was very focused on comparing different wall designs, we now wanted to see what an actual virtual reality experience combined with our EMS prototype would be like. We thus conducted a second study. This time, we gathered only a minimum of Likert scale data, as we were mostly interested in participants' open-ended feedback.

Apparatus
Participants wore the same general type of EMS apparatus as in the first study. However, this time we actuated not

only biceps and wrist, but also shoulders. We also considered both hands, for a total of 6 actuation points (compared to 2 in the first study). In exchange, we left out the vibrotactile actuator, which our first study had found to be of only limited usefulness.

Task and procedure

Participants were outfitted with our EMS device and then underwent the same type of interactive calibration procedure as in our first study. We then placed participants into Rooms 1 and 3 of the virtual world previously described.

There were two interface conditions. In the *EMS condition* the EMS equipment was *on*. In the *baseline* condition the EMS equipment was *off*. Participants thus went through the experience twice (in counterbalanced order). After each run, they filled in a questionnaire.

Participants

We recruited 6 new participants from our institution (1 female, 22.0 ±2.09 years old). Five participants had experienced VR headsets before and two had experienced EMS before.

Hypotheses

We hypothesized that our EMS prototype would lead to a better user experience than the control condition without.

Results

As illustrated by Figure 20, the *EMS* condition received substantially higher ratings. As a matter of fact, *all* participants rated *EMS* higher than *baseline*. This confirms our main hypothesis.

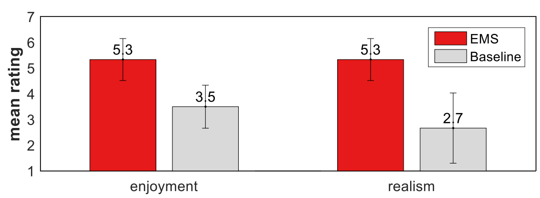

Figure 20: Participants rated their experience in the *EMS* condition higher than in baseline.

Participants also responded to "which object, widget, or effect in the virtual world did you like best and why?" (Figure 21). In the EMS condition, 3 participants preferred the walls ("electrified walls"), 2 participants preferred the cube and one the button. For the control condition, 4 participants preferred the cubes and 2 the button; in the control condition no participant preferred the walls.

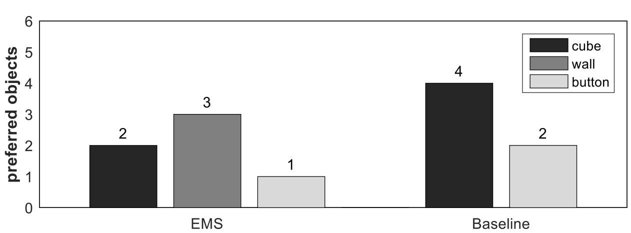

Figure 21: Participants preferred the experience in the *EMS* condition.

We invited participants to comment on their experience. P1 said, regarding the electro wall, "I can't go through this wall", when pointing out the soft walls P2 remarked, "it feels less real (than electro wall) because like this (softer EMS) I can go through". P1 concluded, "I much prefer the sensation *with* EMS—otherwise there is nothing there, just air".

P2 added that the electro walls "added more experience, like better gameplay" and remarked that the "the soft walls were not always necessary, maybe not all switches need it". P2 also added "the cannon (was great) too, but it felt more like a punishment from passing (in front of it)".

P3 stated, "I don't know how VR is supposed to feel but without the EMS it did not seem real at all". Then added, "Also… I could not really grab objects without the EMS, because nothing was there, my hands touched each other". When choosing the button as their favorite object for the baseline condition, P3 remarked, "nothing felt real (without EMS) but at least the button was the only one that was at least kind of realistic". P3 also added that "I immediately felt the difference between an electro wall and a soft wall".

P4 added "The electrified walls worked great—it really felt like touching one. Really surprising." P4 also added "I liked punching the cube at first (without EMS) because it is very (physically) involving, then when I tried it later (with EMS), I felt some impact force; it was great." Later P4 added "the cube is the hardest one to believe, because there are many ways to hold it and it and (the EMS) does not always work that well."

P5 commented with respect to the EMS condition "(The wall) worked great—this was the most realistic element I tried". When P5 experience the same wall without EMS, P5 stated, "oh my… these walls feel really boring". P5's expressed that EMS contributed to simulating walls, buttons, projectile hits, lifting and throwing cubes, but not to punching. P5 explained "I would also like to feel something in my hand, not just the muscles of the arm, it feels misplaced."

P6 stated, "(the) button works great and so do the walls. It feels just right, if I push it, it pushes back and the feeling is continuous". P6 commented about the baseline condition "only the cubes feel right to me because I can manipulate them, the walls and buttons feel wrong". P6 continued "EMS really helped me feel the walls, the button and the projectiles, those really felt strange without EMS, like energy that went nowhere". Lastly, P6 added "the stimulation while operating the cube worked well, but I would have preferred it to push downwards, like pretending to have weight."

Discussion

As expected, EMS added to participants' experience. In particular, participants' responses showed that the "repulsive" wall design using EMS did a good job simulating walls in VR. We also observed, how these walls really stopped participants and participants described them as realistic. In contrast, all participants seemed to agree that walls were *not* realistic in the no-EMS baseline condition. Furthermore, based one participant's feedback regarding the cube ("I would have preferred it to push downwards, like pretending to have weight") we added stimulation to the triceps muscles, hence rendering the cube's weight.

RELATED WORK

The work presented in this paper builds on haptics for virtual reality, in particular tactile stimulation, force feedback, physical props, and electrical muscle stimulation.

Tactile haptics

Vibration is a very common modality in VR because it allows for wearable form factors, such as gloves (e.g., the *CyberTouch* by Virtual Technologies [5]) and vests [21]. It allows conveying the texture of objects [8]. However, it does not allow delivering a *directional* force, which would be required to simulate the force that a virtual object applies to a user's hand.

Other tactile effects besides vibration include skin-stretch [6] and the force feedback illusion created by *Traxion* [30].

Pneumatic Gloves include air pockets that inflate when the user's fingertips touch a virtual object [2]. The *Teleact* glove, for example, featured 30 air pockets around the user's fingers and palm [31]. The technology is also used in surgical manipulators to emulate the experience of touching soft tissue [20]. Another example is *Wearable Jamming Mitten* [32], which locks the user's hand in a clenched position when the user grasps a virtual object. It achieves this by jamming, i.e., by removing all air causing substance inside to interlock (same principle as in [11]).

Passive Haptics in VR

Props. Kohli et al. [18] used props as stand-ins for virtual objects in VR (e.g., to simulate a virtual pedestal in the middle of the room).

Robot arms placing props. Neely proposed using robotic arms for placing props and generating tactile and force feedback for graphics applications [24]. Also, in the system by Yokokohji et al. [37], a robotic arm is used to render the force of pushing against virtual objects in a video-see through reality. Gruenbaum et al. also leverage an industrial robotic manipulator as stands-ins for a control panel of a virtual automobile [12].

Humans placing props. *TurkDeck* [7] employs human actuators to actuate handheld props, including physical walls.

Recently, researchers devised a visual retargeting method for reusing the same prop as a stand-in for different virtual objects [1]. However, this technique only works for similar virtual objects that are closely located.

Forces in VR

Tethers. An approach to providing directional forces is to pull tethers attached to the user (*SPIDAR* [25]). Variations have been used in VR CAVEs to simulate hitting a virtual baseball [16].

Exoskeletons. *Dextrous Hand Master* [14] uses an exoskeleton hand to provide force feedback to the fingers. Other variations of this principle include, for instance, *Dexmo* [13] an exoskeleton for fingers or *FlexTensor* [35], a minimal exoskeleton for the biceps.

SPIDAR-W [26] combines these ideas by mounting a SPIDAR device into a 1.5 x 1.5 x 1.5 m cage that is mounted to the user's body, allowing to scale beyond just fingers.

Also, researchers have combined force-feedback with tactile stimulation. Kron et al. combined a force feedback hand exoskeleton with an eccentric motor on each finger [19]. Similarly, the Data Glove by VPL [10] and Cyber Glove Force by Kramer et al. [17] provide these hybrid force+tactile sensations.

Force feedback using electrical muscle stimulation

EMS originated in the field of rehabilitation medicine where researchers applied electrical impulses to limbs [33]. In Human-Computer Interaction, Tamaki et al. guided users in learning a new instrument (in *possessed hand* [34]) and Pfeiffer et al. used EMS to steer users' while walking [29].

Also, EMS has been used to add force-feedback to mobile devices [22]. Farbiz et al. used EMS on the wrist muscles to render the sensation of a ball hitting a racket in an augmented reality tennis game [9]. Similarly, *Impacto* [23] simulates the sensation of hitting or being hit in VR boxing using a combination of tactile stimuli (a solenoid tapping the skin) and electrical muscle stimulation.

IMPLEMENTATION

To help readers replicate our design, we now provide the necessary technical details.

EMS hardware and calibration

We used the battery-powered, medically compliant 8-channel muscle stimulator (*Hasomed Rehastim*) depicted in Figure 22.

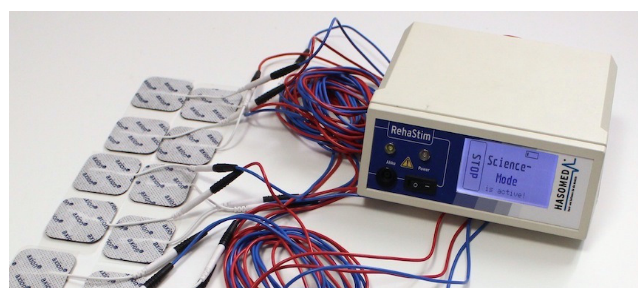

Figure 22: The muscle stimulator we used.

The stimulator is designed for EMS and outputs up to 100 mA per channel. The stimulation is triggered via serial commands using Hasomed's custom protocol, which we generate from inside Unity3D. For each EMS channel, we keep the intensity constant and instead modulate the pulse width (in µs), which we henceforth denote as PWM. This allows us to have greater control (sub-mA) than by varying the current.

Like any haptics system based on EMS, our system requires calibration prior to use. In order to determine what is comfortable for a particular user, we continuously increase the current until we observe a small movement of the targeted muscle. We then let the user calibrate the upper bound that is still comfortable and pain-free. We perform this procedure in the order palm/wrist extensor, biceps, triceps and shoulder rotator muscles.

Electrode placement

Figure 23 depicts the exact electrode placement we used in our prototypes to actuate the user's arm and hand. We placed electrodes on the following muscles: (a) palm and wrist extensors (covering both the *extensor digitorium* and *extensor carpis ulnaris*), (b) biceps, (c) triceps and (d) shoulder external rotators (covering both the *infraspinatus* and *teres major/minor*).

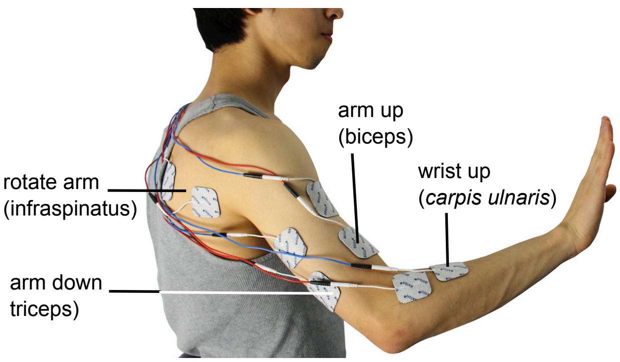

Figure 23: Electrode placement for arm and shoulder.

EMS parameters

Each individual haptic effect, such as the *repulsion* of a wall or the sensation of *picking up* a box has its own specific EMS settings. Values vary across users and should be customized using the calibration procedure described above. Still, here is this data at the example of one of our study participants:

Repulsion wall: palm extensor at 17 mA, 100 µs PWM for 300 ms, biceps at 15 mA and 200 µs PWM for 300 ms.

Soft wall: palm extensor starts at 15 mA and 75 µs PWM, biceps at 15 mA and 70 µs PWM. Here, the stimulation increases linearly as the user presses into the wall or button (function of the distance to the center of object, e.g., a button). The maximum values are 100 µs PWM for the palm extensor and 175 µs PWM for the biceps.

Picking up a box: shoulder muscles at 20 mA and 250 µs PWM and the triceps at 15 mA and 150 µs PWM.

Pushing a box backwards: palm extensor at 15 mA and 100 µs PWM, biceps at 15 mA and 150 µs PWM.

Pushing a box sideways: palm extensor at 15 mA and 200 µs PWM and biceps at 15 mA and 110 µs PWM.

All the aforementioned effects except *repulsion* use a simple linear mapping between the EMS intensity and normalized distance to the object [0=center, 1=surface]. Our intensity-distance mapping is defined as:

$$(\min(\text{intensity}_{\text{maximum}} * (1 - \text{distance}_{\text{normalized}}) * \text{growth}_{\text{factor}}) + \text{intensity}_{\text{offset}},\ \text{intensity}_{\text{maximum}})$$

When *pushing a box backwards* or *sideways*, the applied mapping is steep (hence, growth factor is 2) since the effect should be strong upon contact with the object. However, in the *Soft Wall* the intensity build up is softer, hence the growth factor is kept at 1. When *picking up a box* the growth factor used is also 1; note that on the triceps, the intensity offset is calibrated higher than for the other effects as to constantly simulate the cube's weight as soon as the user grasps it. Lastly, the *Repulsion* effect does not utilize such a mapping because it is only active for 300 ms.

VR engine

We implemented our virtual worlds in *Unity 3D*.

Tracking

We track the user's headset and hands using rigid body optical markers and cameras (8x *Optitrack's Prime 17W*) covering a tracking volume of 4.5 x 4.5 x 3m. When replicating our system, an HTC *Vive* would be equally suitable.

Our system determines collisions between the user's hands and virtual objects using collider objects in Unity. This triggers the respective muscle stimulation patterns by sending a message to a server application that communicates to the EMS device. This allows us to decouple the UI and the EMS hardware, allowing it to run on any device regarding of its serial capabilities.

CONCLUSIONS

In this paper, we presented a new approach to rendering the haptics of heavy and stationary objects, in particular by means of electrical muscle stimulation. This is our main contribution. We also achieve this in a wearable form factor, suitable for real-walking VR environments.

As future work, we plan to explore this approach in *augmented* reality. Since our approach leaves the user's fingertips free to touch physical objects and physical walls, our technology should be a good match for AR.

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