Adding Force Feedback to Mixed Reality Experiences and Games using Electrical Muscle Stimulation

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ABSTRACT
We present a mobile system that enhances mixed reality experiences and games with force feedback by means of electrical muscle stimulation (EMS). The benefit of our approach is that it adds physical forces while keeping the users' hands free to interact unencumbered—not only with virtual objects, but also with physical objects, such as props and appliances. We demonstrate how this supports three classes of applications along the mixed-reality continuum: (1) entirely virtual objects, such as furniture with EMS friction when pushed or an EMS-based catapult game. (2) Virtual objects augmented via passive props with EMS-constraints, such as a light control panel made tangible by means of a physical cup or a balance-the-marble game with an actuated tray. (3) Augmented appliances with virtual behaviors, such as a physical thermostat dial with EMS-detents or an escape-room that repurposes lamps as levers with detents. We present a user-study in which participants rated the EMS-feedback as significantly more realistic than a no-EMS baseline.

Author Keywords: games; mixed reality; EMS;

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

INTRODUCTION
Augmented Reality and Mixed Reality (AR/MR) interfaces allow displaying virtual information to the human senses while users explore the real world [16,44]. Researchers explored MR to overlay data [63], assist in maintenance tasks [49,20] and virtually recreate physical games [31].

As the next step towards realism and immersion, many researchers argue that MR systems should also support the haptic sense in order to convey the physicality of the virtual world [64], to better "blend" both realities [44, 22] and to increase the user's sense of agency [42].

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Unfortunately, not much of the existing haptic technology applies to Mixed Reality. While Virtual Reality (VR) users have access to haptic gloves and exoskeletons with tactile [6,57] and force feedback [17, 23], the main challenge for MR is that users may encounter not only virtual objects, *but also physical objects*. This means that haptic technology for MR must leave the users' hands unencumbered [64]. Furthermore, MR users may want to avoid any kind of bulky technology, as these tend to be visible in MR and in extreme cases might even occlude the real-world objects users are trying to interact with.

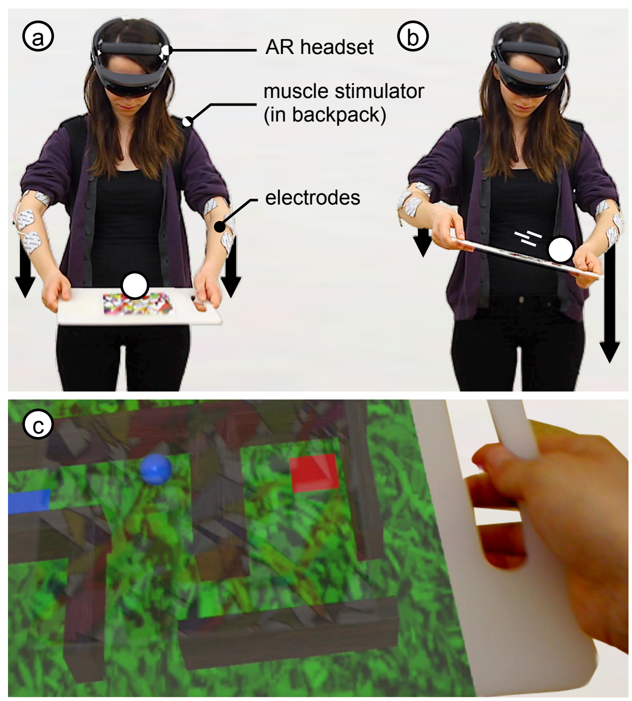

Figure 1: (a) In this Mixed Reality game that uses a physical tray as prop, our mobile system renders shifts in the tray's center of gravity as the marble moves. (b) Our system creates the necessary forces by applying electrical muscle stimulation to users' triceps muscles. (c) Our approach leaves users' hands free at all times, allowing the user to interact with the tray.

While some researchers have proposed ways to simulate the *tactile* qualities of objects in MR, e.g., by vibrating the user's fingernails instead of the fingertips [1], simulating the physical resistance of objects continues to be a challenge. The reason is that the standard solutions based on mechanical actuators such as exoskeleton gloves [17, 60] and wearable pulley systems [46] tend to be large and cumbersome.

In this paper, we propose adding force feedback in MR games and experiences using electrical muscle stimulation instead—an approach that is small, light, and fits under the user's clothing. Figure 1 illustrates this at the example of our Mixed Reality balance marble game using a physical tray as a game prop, which our approach augments via EMS-based force feedback. Using EMS our simple game is able to, for instance, render shifts in the board's center of gravity, caused by the "weight" of the moving virtual marble, by actuating the user's arms towards the heavier side.

We demonstrate, by means of four simple mixed reality experiences built for the Microsoft HoloLens, how EMS supports force feedback not just in VR (as previous research demonstrated [41, 37]) but also in the broader spectrum of Reality. This includes adding force feedback on a variety of situations rooted in the Reality-Virtuality continuum [43], ranging from interacting with purely virtual objects, to passive props and augmented physical devices.

WALKTHROUGH OF A MIXED REALITY EXPERIENCE

Figure 2 shows a user wearing our EMS for Mixed Reality system. The user is wearing a Microsoft HoloLens headset that runs yet of our stand-alone and untethered experiences, here an interior design application. The user is exploring what light bulb might illuminate her painting best. She uses a regular cup as an impromptu tangible brightness dial to explore different light settings. The HoloLens displays the associated GUI. As she tries to increase brightness past the allowed maximum, the system actuates her wrist rotation muscles by means of EMS, preventing her wrist to go past the maximum and she hits a hard stop.

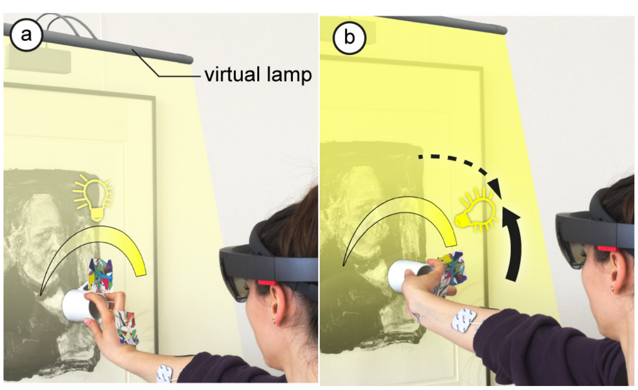

Figure 2: Using a regular cup as an impromptu tangible brightness dial. (a) When she tries to increase the brightness past the allowed maximum, her hand hits a hard stop. (b) Our system renders this constraint by applying EMS to users' wrist muscles.

Figure 1a shows the system she is wearing, i.e., an EMS signal generator connected to electrodes placed on the user's wrist, arm, and shoulders—leaving her hands free to interact with physical objects at all times. The system wirelessly interfaces with the MR headset. It is wearable and fits into a small backpack. Figure 3 shows the user's view through the HoloLens. In the interest of visual clarity, we show subsequent images in a 3rd person perspective. Figure 3b highlights one of the markers we are using in *some* of our examples—a stopgap measure to obtain the *orientation* of props and of the user's hand (see "Implementation").

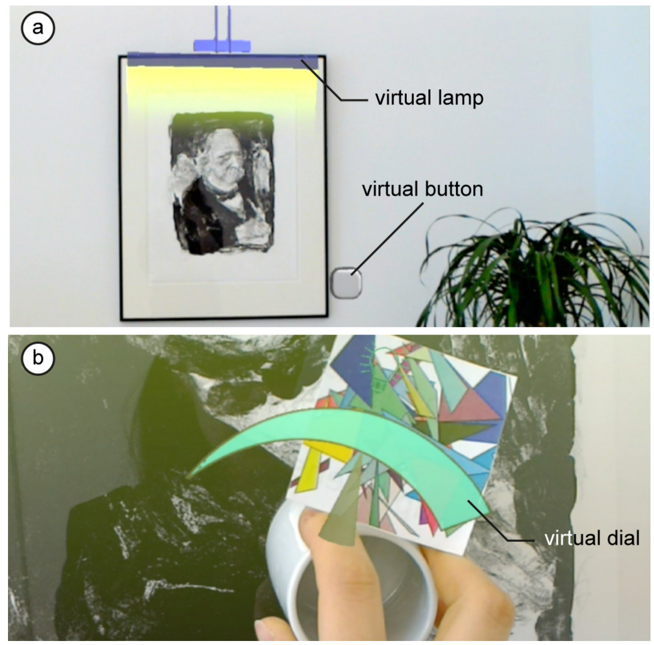

Figure 3: The previous scene through the HoloLens.

Figures 4-8 show a slightly longer walkthrough of the interior design experience. Here, our user is configuring furniture for her future living room, which includes a couch and a lamp specifically tailored to highlight a valuable painting on the wall. We designed the walkthrough to showcase examples from three classes of objects on the reality-virtuality continuum [43], ranging from fully virtual to physical objects.

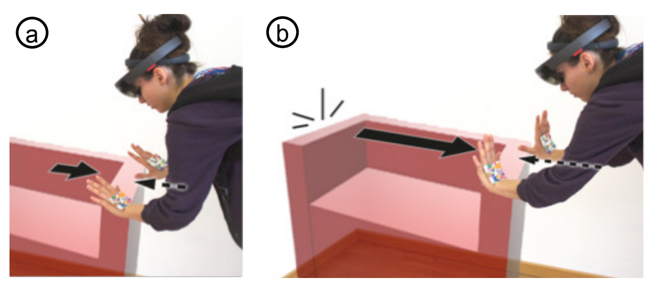

Figure 4: (a) This user physically drags the couch and feels the simulated friction against the floor. (b) As the couch collides with a real wall, the system stops the user by pushing the user's shoulders and wrists backwards.

1. Providing virtual objects with force feedback. Figure 4 shows the user exploring different placements in the room by pushing a couch with her two hands.

Our system renders the couch's friction against the ground as a gentle force pushing her hands back, by stimulating the user's shoulder muscles (Figure 4a). Lastly, when the virtual couch hits the real wall, the EMS force feedback increases and informs the user of the collision (Figure 4b).

Virtual mechanisms. As illustrated by Figure 5, the user now explores a lamp from the catalog. After placing gallery lighting so as to highlight the painting on the wall, the user turns the lamp on by pressing the switch. Here our system renders the button's mechanics using force feedback. When the user presses the switch to turn the lamp on, she feels the constant counterforce of the spring inside the button until the button is fully depressed and it latches (Figure 5b). To achieve this effect our device primarily actuates the user's wrist, complemented as well with some light actuation on the shoulder.

Figure 5: Turning on the virtual lamp. Here our EMS system renders the forces of the button's mechanism.

Also, when pushing the switch while it is on the "on" position (button depressed inside), our system applies a weak force feedback until the switch is pressed. The virtual spring then releases at full force as the user's hand is pushed backwards. This is an example of how EMS recreates the expected physics of objects (e.g., a spring and latch), so as to better align the virtual and the real in Mixed Reality.

2. Turning passive props into impromptu tangibles using EMS. The user now configures the brightness of the lamp. As shown in Figure 6, the user picks up a cup to serve as a tangible brightness dial. The system extracts the dial's rotation and maps it to the brightness of the lamp. The lamp's intensity is displayed as a halo visually projected onto the scene. Our system adds physical constraints, preventing the user from rotating past the minimum and maximum values. We render these constraints by stimulating the user's wrist rotator muscles so as to provide a counterforce to the user's direction of turning, thereby stopping the user's twist.

Figure 6b shows how our system also adds detents to the dial. These detents inform the user that the selected intensity is available as a light bulb, while values in between require an extra dimmer. Our system renders the effect by stimulating the antagonist muscle with brief pulses, i.e., when the user rotates the dial clockwise the system sends short pulses that turn counter-clockwise and vice-versa.

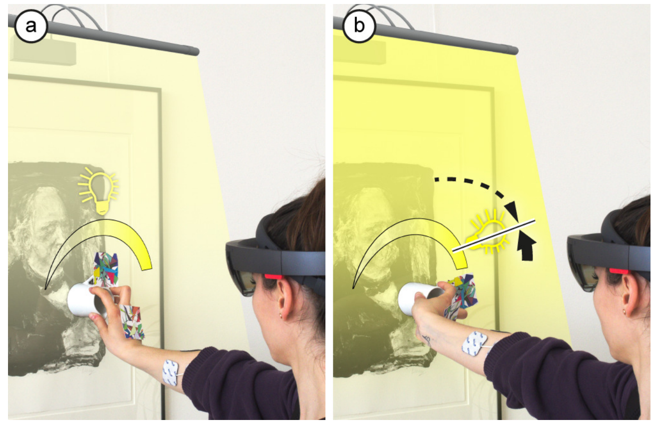

Figure 6: The user configures the intensity of the desired light bulb using a cup as a stand-in for a dial (passive prop). Using EMS force feedback, our system augments the tangible with constraints and detents.

Physically linked passive props. Now, the user realizes this light's color temperature is too warm for her artwork. Hence, this time, she places two cups, the left represents light temperature and the right one stands for intensity (Figure 7a).

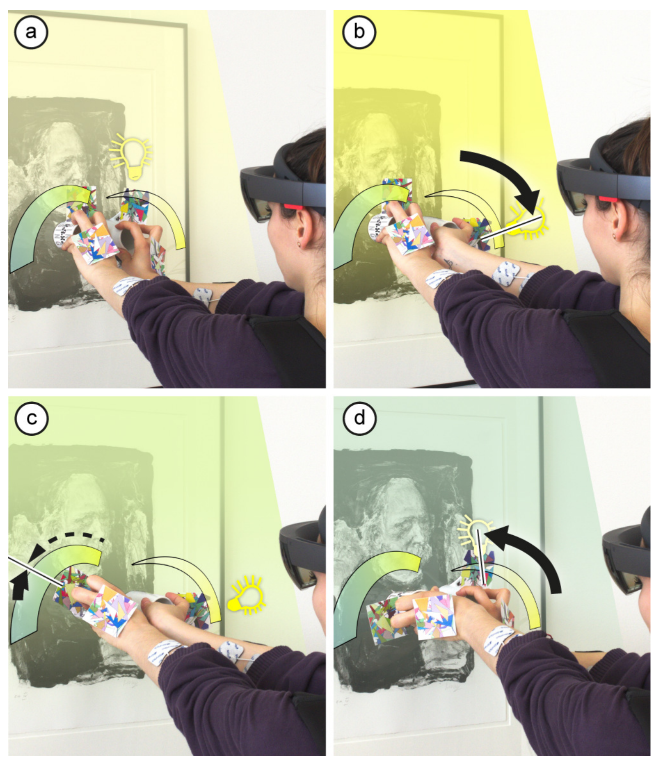

Figure 7: The user manipulates two cups to control the light temperature and intensity simultaneously.

Since she previously left the intensity value at maximum, as soon as the system recognizes the cup, it actuates her wrist rotator muscles to place the dial back in the last used value (Figure 7b). We do so to align virtual and physical worlds into a coherent mixed reality. Then, she explores combinations of different light color temperature and intensities bimanually. These two parameters are dependent in that bulbs are available only in certain intensity-temperature combinations. Changing one parameter (e.g., light temperature) causes the system to adjust the other (e.g., intensity) to achieve an existing option in the catalog. In the Figure 7c, for example, the user chooses a "colder" light, causing the system to switch to a less intense bulb by actuating the user's wrist as to reach that option (Figure 7d).

3. Augmenting real objects. Finally, the user decides whether to upgrade her thermostat to a better model offered in the catalog. The better thermostat offers detents that inform users about the most recently used temperature setting. Here, our system simulates the new thermostat by virtually enhancing the existing thermostat with the missing feature. The user explores this new "version" of the thermostat and decides to order one.

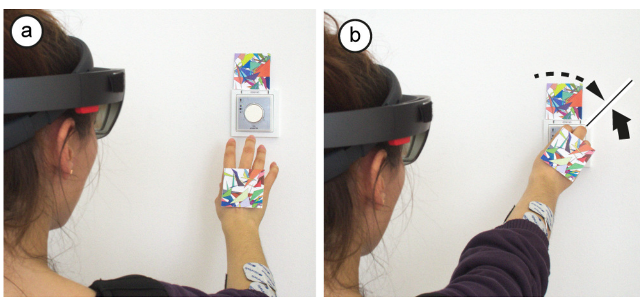

Figure 8: Here, our system enhances a fully functional thermostat with detents.

SUMMARY OF WALKTHROUGH

As mentioned earlier, the examples in our walkthrough were chosen to illustrate how our system covers Milgram et al.'s reality-virtuality continuum [43] shown in Figure 9.

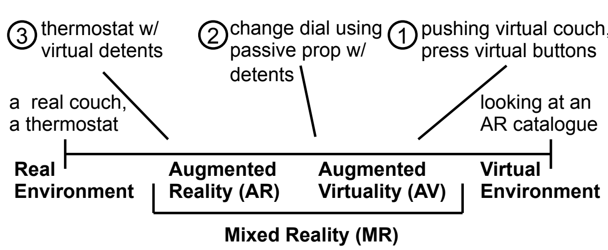

Figure 9: Walkthrough examples mapped to the reality-virtuality continuum by Milgram et al. [43].

Starting from the right, we (1) provided EMS-based force feedback to fully virtual objects, here a couch. (2) We then provide EMS force feedback to objects augmented with passive props. We used this to provide these objects with additional physical properties, here detents and constraints to a dial. (3) Lastly, we augmented a physical device with an additional property, here a thermostat enhanced with detents.

EMS IN MIXED REALITY GAMES & EXPERIENCES

As discussed earlier, we think of this as a system that enables physical feedback in Mixed Reality, not only limited to the aforementioned walkthrough scenario (i.e., interior design). To emphasize this point, here are three other immersive experiences that we made using our system, each highlighting a step of the reality-virtuality continuum:

1. Purely virtual: shooting the catapult

Figure 10 shows a simple MR game featuring a virtual catapult that appears in the user's physical surroundings. (a) The user arms the catapult by pulling the catapult's bucket backwards. We implemented this example without markers, instead using HoloLens' "pointing". As the user pulls the bucket backwards, our system provides force feedback that simulates the increasing tension of the catapult—this force feedback also serves as an indicator for the user on how far the projectile can be expected to fly. Our system achieves this by stimulating the antagonist muscle (triceps) proportionally to the catapult's arm angle. (b) When the user opens the hand (which terminates the HoloLens gesture) the catapult releases. Our system abruptly ceases to stimulate the triceps ceases and the remainder force in the user's biceps, which now does not have a counter force, creating a sensation of actual recoil.

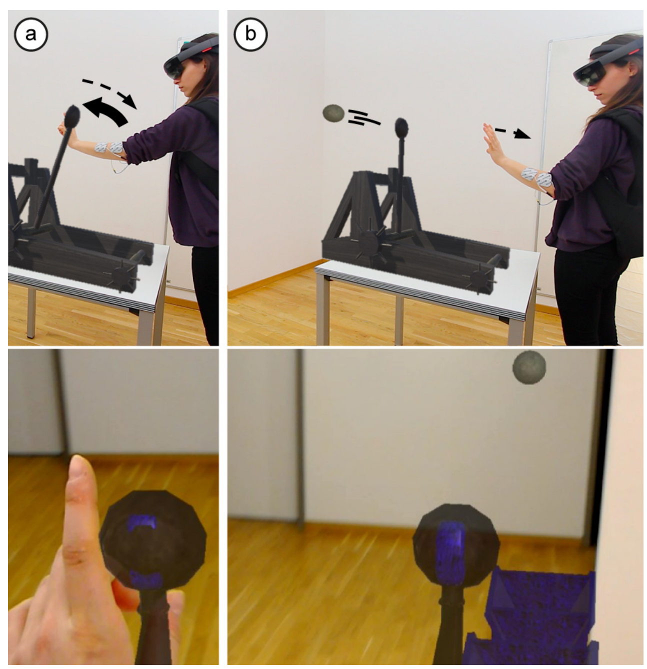

Figure 10: While the user pulls the lever of this virtual catapult, our system provides force feedback simulating the catapult's spring.

2. Augmented physical props: balance marble game
Figure 1 depicted a classic MR marble maze, which was in fact inspired by that of Ohan and Feiner [48] and complemented with EMS-based force feedback for added realism. As previously explained, our marble game renders the shift in gravity caused by the moving marble by actuating the user's arms towards the heavier side. Note that even if the marble perfectly balanced on the center of the tray we render a constant pull down of the user's arms (triceps) to represent the marble's weight under gravity.

Furthermore, we render a number of extra haptic effects: (1) when the ball collides with any of the maze walls, we render a short bump in the user's triceps, depending on the ball's velocity vector; (2) when the marble falls out of the tray in one of the openings in the obstacle walls, the user feels the relief in the weight; and, (3) when the game starts, the marble falls from the sky onto the tray and we render this "extra weight" by quickly pulling down the user's arms , as depicted in Figure 11.

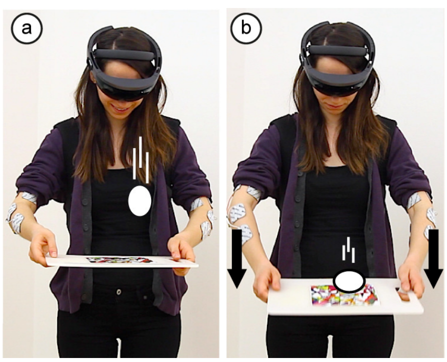

Figure 11: (a) At the start of the game the marble falls from the sky. (b) As it hits the tray, the EMS pulls the user's arms down quickly so as to represent the impact.

3. Augmented appliances: escape room experience
We implemented a simple *Escape Room* [14] experience in Mixed Reality. In the traditional version of these experiences, users must first find the solution to a puzzle, and only then they can escape the current room. Figure 12 illustrates the user solving this room's puzzle.

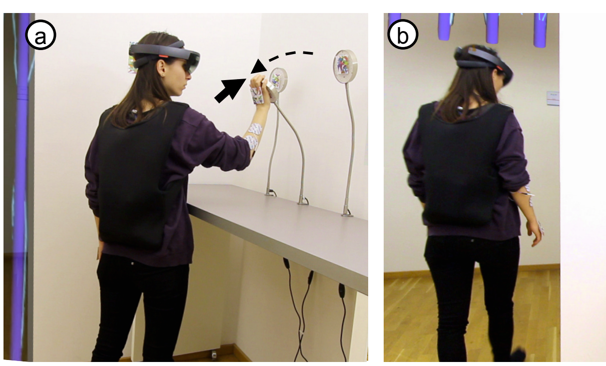

Figure 12: (a) These gooseneck lamps are repurposed as levers, with force feedback, allowing the user to input the secret combination to (b) unlock the door.

The user sees a virtual message on the wall next to the virtual door that provides a clue to the puzzle: "the lights will illuminate your path, but only in one special way". The user now explores one of the three suspicious gooseneck lamps in the room. As shown in Figure 12, the user finds that when moved the lamps have detents, rendered using our system, hence they can be only in one of three positions. By testing different positions, the user finds the secret combination of the lamps' gooseneck positions that opens the virtual door.

CONTRIBUTION, BENEFITS & LIMITATIONS
We propose the use of EMS for force feedback in Mixed Reality. The main benefit of our approach is that it leaves users' hands free, thus allowing users to interact unencumbered—not only with virtual objects, but also with *physical* objects in the user's surrounding, such as props and appliances. We demonstrate this approach by sampling it at several points across the reality-virtuality continuum.

The benefits of our system, which have been validated in our user study, are: (1) providing force feedback to MR provides users leads to a better understanding of the virtual object's state. (2) This haptic information is especially useful because the current headsets have a limited field of view. (3) The addition of force feedback to MR games and experiences increases the perceived realism.

Our system is subject to the limitations of EMS systems: (1) it requires electrode placement and per-user calibration prior to use, (2) it can cause muscle fatigue, (3) and the actuation of hands is typically limited to a single dimension of translation. Also, in order to keep our rendered haptic effects robust to work for all our participants, we opted for fairly simple output gestures (extension of wrist, rotation of wrist, and so forth). Furthermore, our current implementation based on HoloLens has a limited field of view and requires markers to track the orientation of the users' hands and physical objects. Lastly, while our approach is the first step towards mobile and unencumbered force-feedback in MR, its current form lacks integration with tactile feedback on the fingertips, which we discuss later.

RELATED WORK
Our approach builds on work in haptics, in particular tactile feedback, force feedback, passive haptics, and electrical muscle stimulation.

Tactile feedback
Haptics is subdivided into cutaneous feedback (e.g., tactile) and proprioceptive/kinesthetic feedback (e.g., force and position) [18]. Tactile feedback allows simulating properties of touching or grasping an object, such as texture, vibration and pressure [18].

Vibrotactile actuators pressing against the user's fingertips are the main approach to simulate the texture of objects [11]. Researchers typically embedded these into gloves [6] or vests [35]. Other tactile approaches include pressure, e.g., pneumatic gloves, such as the *Teleact* [57], which inflate air pockets against the user fingertips. These typically inform the user when they contact a virtual object [3]. The *HapThimble* combines these two approaches (vibrotactile and pressure) by pushing a vibrotactile actuator against the user's fingertips [30]. Also, skin stretch actuators are used for simulating directional forces when contacting objects [9, 5]. These work by stretching the user's finger pad skin using actuators such as steward platforms [30] or pulling cables [4]. Lastly, alternative techniques such as ultrasound beam forming are gaining more popularity for tactile stimulation [8].

The main challenge for tactile feedback in Mixed Reality is to make these technologies leave at least the user's fingertips, or even better, leave the entire hands free to touch physical objects. For this, Ando et al. proposed shifting the position of the vibration actuators from the fingertip to the back of the nail [1,2]. This design has the advantage that it keeps the user's fingertips free to "feel the environment directly" [1]. As we discuss in the future work, it might be worth combining this fingertip-free tactile approach with our hands-free force-feedback approach.

Force feedback

The type of haptics we explore in this paper is force feedback, i.e., simulating the force arising from the contact with a virtual object, which is sensed by the user's proprioceptive system [18].

Grasping manipulators: A large category of work in force feedback revolves around devices that make users hold on to a handle, which is then actuated by a robotic arm (e.g., Phantom [25]) or by pulley systems (e.g., *SPIDAR* [45]). These were used to simulate touching [10] or colliding with virtual objects [29], and object's properties such as stiffness [25] or weight [56].

Exoskeletons: These mechanically actuated devices provide forces by pulling the user's limbs against the mounting point on the user's body. Exoskeletons are mostly used to actuate the user's arms [60] or wrists and fingers [23, 17]. The latter glove based exoskeletons typically anchor to the base of the user's wrist and tether to the user's fingertips. Hence, as discussed earlier, these interfere with the user's grasping and touching. Similarly, the *SPIDAR-W* [46] is a version the aforementioned SPIDAR device mounted into a frame that the user carries around. Here, the cables for the pulleys interfere with the user's hands.

Passive haptics

Because our approach leaves the user's hands free, it harmonizes well with *Passive* Haptics. Passive haptics leverages inert physical objects to simulate the properties of virtual ones (e.g., touch, shape, weight) [27].

Hand-held props are often repurposed as passive haptics since these provide tactile cues for virtual experiences. For instance, Hinckley et al. utilized props so as to provide users with physical controllers for neurosurgical visualizations [21]. Lindeman et al. gave users physical tablets as stand-ins for the surface of a hand-held menu [33].

Tangibles are often employed in the same way so as to simulate the missing physicality of virtual control panels such as [6] or as in *tangible bits* by Ishii et al. [28]. Lastly, *opportunistic controls* [9] by Henderson and Feiner leverages natural affordances as tangible user interfaces for augmented reality (e.g., the collar of an antenna connector becomes a physical dial). In *Annexing Reality* passive props are used as stand-ins for objects in augmented reality [22].

In fact, our approach takes inspiration from *Annexing Reality* and *Opportunistic Controls* but goes further by using EMS to actuate the seemingly passive props and provide them with constraints.

Providing physicality in the reality- virtuality continuum

Other researchers have been working on providing passive haptics feedback to the different stages of the reality-virtuality continuum [43]. For instance, *One Reality* [54] is an interactive desktop system that allows users to work directly on their work piece in the different stages of the continuum: purely virtual (VR), to VR with passive props, to full projection mapping with passive props, etc. However, their system is not mobile nor does it affords force feedback.

EMS-based haptics

Electrical Muscle Stimulation (EMS) has been actively researched since the 1960s in rehabilitation medicine as a means to restore lost motor functions, e.g., after spinal cord injuries [59]. In the 1990s, artists started to utilize EMS as well. Stelarc, for example, used EMS as a simple form of teleoperation between a human arm and a robotic arm [12]. Only more recently, researchers in HCI started to explore EMS, e.g. Kruijff et al.'s EMS desktop gaming [32] or the *Possessed Hand* [60].

One of most popular research areas of EMS in HCI is towards increasing realism. Farbiz et al. applied stimulation to the wrist muscles so as to render the sensation of a ball hitting a racket in a simple augmented reality tennis game [15]. In *Muscle Propelled Force Feedback* [36] researchers demonstrated how EMS could be used as a miniaturized form of force feedback making it applicable to mobile gaming. In *Impacto* [37] researchers demonstrated how to create the sensation of hitting or being hit in VR boxing by using a combination of EMS and a solenoid taping the user's skin. Lastly, Lopes et al. extended this approach to simulating walls and heavy objects in VR [41].

Our current paper extends these works by bringing EMS to the larger scope of Mixed Reality, which includes not only virtual content, but more importantly, allowing to actively repurpose everyday objects, appliances and passive game props into active constituents of the user's MR experience.

IMPLEMENTATION

To assist readers in replicating our design, we now provide the necessary technical details and the complete source code[1]. The latter allows the community to build EMS enabled applications, which are decoupled from the headset technology by providing an EMS library for Unity3D.

Hardware

We implemented our system using a Microsoft HoloLens MR headset [24] and a medical-grade muscle stimulator shown in Figure 13. The interface between these components is a laptop computer running Windows 10 that the user carries in a slim backpack. The laptop is required only to offer a USB to connect the muscle stimulator (so headsets with USB connectivity would require no laptop).

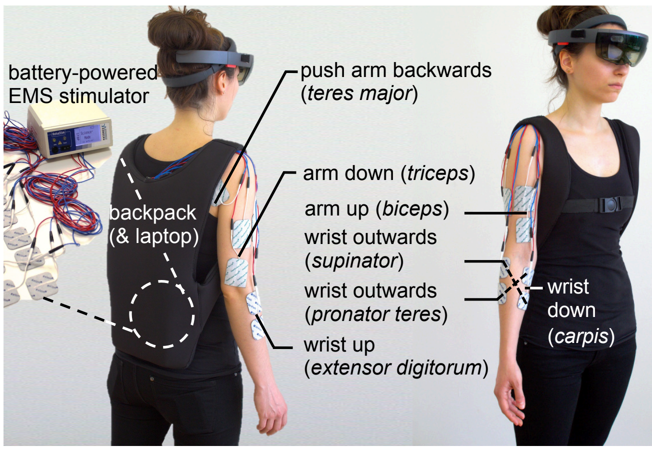

Figure 13: The hardware components and electrode placement (one arm only).

Electrode placement

Figure 13 details how 10 electrodes are placed on the user's right arm and shoulder; the user's left arm is equipped the same way. This set-up allows our system to achieve the following motions: (1) wrist extension (*extensor digitorum*), (2) wrist flexion (*flexor carpi radialis*), (3) wrist pronation (*pronator teres*, achieved with the base electrode of wrist extension and end-point of wrist flexion), (4) wrist supination (*supinator*, achieved using both base electrodes of the wrist extensor and flexor), (5) elbow flexion (*biceps*), (6) elbow extension (*triceps*) and (7) pushing the arm backwards via the shoulder (*teres major*).

Calibration

To calibrate the system, we (1) start from zero and increase the amplitude of the EMS until we observe a small movement of the muscle. (2) We ask the users themselves to slowly increase the amplitude up to an upper bound that is still comfortable and pain-free while clearly performing the expected gesture. (3) To test the calibrated gesture under realistic conditions, we ask the user to move the arm and we apply the calibrated gesture mid-way. Then, if needed, we re-adjust the intensity to match the expected outcome. This helps our system perform well despite varying arm poses, which tend to occur during real walking. (4) We then, upload these intensity values to our system. (5) We repeat this procedure for all muscles stimulated in our MR games and experiences.

[1] https://hpi.de//baudisch/projects/ems-ar-haptics.html

Muscle stimulation parameters

We now describe the parameters of our EMS effects, as used in our games and experiences. Since the intensity values are user-dependent we provide these at the example of the parameters for one of our study participants:

Haptic Effect	Muscle	mA	µs	Muscle	mA	µs	Duration
Impulse/Impact (i.e., quick force in the opposite direction of motion)							
Detents on Dial & Slider	Wrist rotator	15	200	-	-	-	150
Detents on Lever	Triceps	17	265	-	-	-	150
Marble hits walls	Triceps	18	290	-	-	-	300
Marble drop	Triceps Right	17	280	Triceps Left	17	280	300
Spring (i.e., continuous counterforce with spring coefficient)							
Button	Shoulder	27	280-350	Wrist extens.	15	100-150	Proportional
Catapult	Triceps	17	200-275	-	-	-	Proportional
Friction (i.e., continuous counterforce)							
Couch Static friction	Shoulder	27	100-420	Wrist extens.	15	100-200	Ramp up
Couch Kinematic Friction	Shoulder	27	300	Wrist extens.	15	120	Cont.
Limits (i.e., strong counterforce that stops motion entirely)							
Dial maximum position	Wrist rotator	15	265-300	-	-	-	Ramp up
Weight/Gravity (i.e., constant and continuous force)							
Marble weight	Triceps Right	17	200	Triceps Left	17	200	Cont.
Marble shift	Triceps Right	17	265	Triceps Left	17	265	Proportional

Figure 14: Stimulation parameters per haptic effect at the example of one study participant: amplitude (in mA), pulse-width (in µs) and duration (in ms).

Hand tracking

Our system's primary way of tracking users' hands is HoloLens' built-in visual tracking. When HoloLens recognizes the point gesture (fist closed and index pointing up) and it reports the 3D position of the center of the hand to our application. Our application applies this position to a representation of the hand (a box collider), which is also the boundary we test for collisions with other virtual entities.

Several of our application examples, e.g., catapult or pushing furniture, run based on HoloLens' tracking alone. However, for others we added *Vuforia* passive AR markers [62] to the back of the user's hands, as shown, e.g., in Figure 3b. These help us overcome two current issues with HoloLens' hand tracking (Version 1, Development Kit 2016): (1) hand tracking fails when the user's hand comes close to a real-world surface and (2) the HoloLens API reports just the position of the hand, but no orientation.

Mapping virtual to physical space

In order to attach virtual contents to locations in the physical room, our system uses HoloLens *spatial mapping* feature [11]. Our system also utilizes the *HoloToolkit-Unity* library alongside its *Spatial Understanding* module during runtime to identify surfaces to place the virtual objects.

Event handling

Our system processes events as follows. (1) When our system running on the HoloLens determines a collision between the user's hand and a virtual object by means of a Unity *Collider*, it (2) determines the parameters of the muscle stimulation based on the physics properties of the virtual object (weight, friction coefficient, springs) that the user is interacting with. Pushing a couch, for example, produces a stronger haptic effect than pushing a button. (3) Our system generates the message for the EMS stimulator and (4) sends it via UDP to the laptop. (5) The laptop, which is running a simple Unity3D UDP server, receives this message and (6) relays it in a Serial format (via USB) to the muscle stimulator. (7) This triggers the stimulation.

Technical limitations of our prototypes

While, to our knowledge this is the first functional mobile implementation of EMS in Mixed Reality, there are a number of limitations in the current prototype.

Given that the HoloLens does not provide a USB port, there is some latency in the wireless implementation: detecting collisions in Unity (~20-30fps), sending EMS commands wirelessly to the stimulator (<10ms) and in detecting the hand's position via Vuforia (~20fps). However, note that our participants did not remark on perceived latency while commenting on their experiences.

On the haptics side our prototype is limited only to force-feedback, allowing users to feel the boundaries of objects as well as forces arising from interactions but does not render any textures on the fingertips. However, it does render some basic physics of objects (even beyond just soft vs. hard as in [51]), for instance: the force of the spring inside the button, the couch's static friction is larger than its kinematic friction, the couch being softer in middle than at the arm rest and so forth.

Lastly, our games are currently based on the HoloLens room tracking, i.e., these require the HoloLens to recognize the current room [24]. Within a room, the full interaction area is available for EMS feedback as long as users' hands are inside the HoloLens front-facing hand tracking area.

USER STUDY

The objective of our experiment was to assess whether EMS-based force feedback in MR increase users' sense of realism. Participants performed three simple tasks, directly derived from our aforementioned applications. Participants performed each task using an EMS-based condition and a no-EMS control condition. We hypothesized that EMS would lead to higher ratings on both realism and enjoyment.

At this initial stage of exploring EMS in MR games, we opted for a study focused on the realism of the proposed haptic effects. In order to do so, participants were instructed to explore the EMS-induced physical sensations rather than to perform the task at maximum speed. As such, our study does not provide insights into task performance.

Apparatus

Participants wore the HoloLens and our EMS backpack-based setup discussed earlier and depicted in Figure 13, which allowed for untethered use. We calibrated the EMS setup as described earlier (see "calibration"). Participants experienced the sound effects of each task via the HoloLens headphones.

Interface conditions

EMS: force feedback by means of EMS.

no-EMS: participants received no force feedback (control).

Tasks

(1) *furniture.* Participants performed a simplified version of our walkthrough in which they were asked to rearrange a virtual lamp on the table to properly light a physical book and to align a virtual couch with the room's wall.

(2) *catapult*. Using our catapult, participants tried to hit two targets at different distances.

(3) *marble*. Participants played the marble balance game in three levels of increasing difficulty.

Note that to keep the study concise and under one hour we excluded the escape room experience.

Procedure

Each participant performed all three tasks in both EMS and no-EMS condition (within-subject design). Both the condition and task order were randomized. After each task, participants rated their experience in terms of *realism* (1: artificial, 7: realistic) and *enjoyment* (1: not at all, 7: very much). After all tasks, we asked participants, which interface condition they preferred for each task and gave them an opportunity to provide open-ended feedback.

Participants

We recruited 12 participants (2 female, $M = 22.7$ years, $SD = 4.9$) from our local institution. Two out of the 12 participants had tried a HoloLens at a technology fair. One participant had previously experienced EMS at their local gym. With their written consent, we videotaped the study sessions and transcribed their comments.

Results

We analyzed the data using a 2 (*condition*) × 3 (*task*) repeated measures ANOVA (α = .05) as suggested by [47]. All pairwise comparisons were Bonferroni-adjusted.

Figure 15 shows participant's average ratings in both conditions regarding perceived realism. We found a significant main effect on interface ($F_{1,11}$ = 46.112, p < .000). Pairwise comparisons revealed that perceived realism was higher in the EMS conditions, for every task.

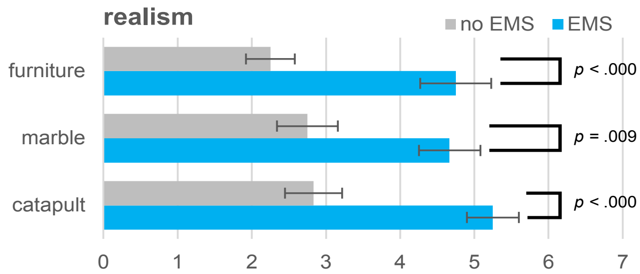

Figure 15: Participants rated their experience as more realistic in the EMS conditions.

We also found a main effect of the interfaces on enjoyment ($F_{1,11}$ = 17.135, p = .002). As depicted in Figure 16, participants rated the enjoyment significantly higher when in the EMS condition for the *furniture* and the *catapult tasks*.

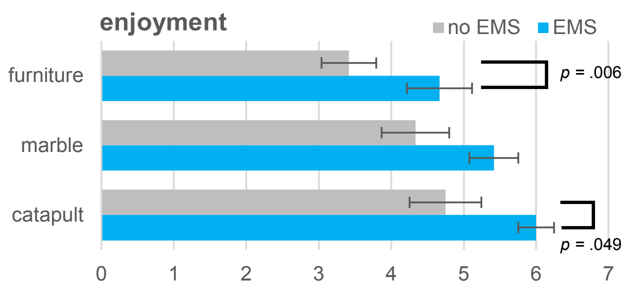

Figure 16: Participants rated their experience as more enjoyable in most of the EMS conditions.

Figure 17 summarizes participants' preferences for each of the interface conditions. For the *furniture* and the *catapult tasks*, 10 out of 12 participants preferred the EMS interface condition, for the *marble task*, 7 out of 12 preferred EMS.

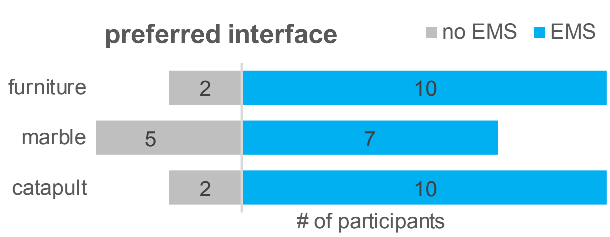

Figure 17: Most participants preferred the EMS to the no-EMS interface condition across tasks.

Qualitative results

Throughout the experiment participants often voiced their explanations for what they felt, albeit not being instructed to do so. We summarize these:

Pushing furniture: When pushing the lamp and couch most comments revolved around how the EMS aligned with their expectations of the physics of such objects, such as friction, weight, and collisions. For instance, P5: "I immediately feel when I touch something [shows us touching the couch], even though I know this [couch] is not here" (similarly P6, P9, P10). P2 noted "pushing the lamp and couch felt much better than I ever expected, it's like you feel the weight, and the couch was heavier". P5 "did I feel friction? I think I felt friction when pushing it [the lamp] on the table". P3 "was super real to push the lamp, only in the end I realized that when the lamp hit that thing [bump] on the table, I had to push stronger against the muscle stimulation to make it pass it" (similarly, P9, P10 and P12).

Furthermore, seven out of 12 participants remarked how, in their opinion, EMS had helped them overcome the HoloLens' limited field of view. For instance, P5: "the muscle feedback makes pushing the couch much easier, (…) I could not see if it was hitting the wall, but I could feel it".

Balancing the marble using the tray (Figure 18) polarized participants in that only 7 of them expressed a preference for experiencing it with EMS. Not remarkably, 8 participants remarked that the EMS added difficulty to the game, because not only they had to steer the marble, but they had to do it against the force feedback. P8 remarked, "[EMS] makes it feel like a heavy ball when it pushes me down (…) but when it pushes me to the side it makes the game harder and more confusing". In contrast, P5 commented "this [EMS] makes the marble motion realistic, [and thus] the game is now much nicer to play".

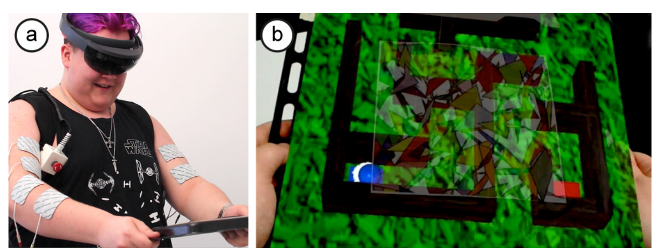

Figure 18: Participant balancing the marble (image from the study, with consent of the participant).

Catapult All participants voiced positive remarks about the catapult, which might explain the highest rating for both realism and enjoyment. P9 noted "Ah, now I feel the catapult's arm", when trying the catapult with EMS after trying without. Similarly, P2 noted "it helps me to know how far I will shoot, because I feel the amount of [EMS] feedback is related to how much I pull". P1 noted "without EMS the catapult is no fun because it becomes a memory game, you learn the correct angle and just hit the targets". P8 stated "this is how I think pulling a catapult feels like".

Open-ended feedback. P3, P5, P6 and P7 expressed their appreciation for the physical objects we had integrated into the MR experience, e.g., "I like touching these real things [points at the book on the table, the wall and the tray] and feeling they are now part of the VR" (P7). When we asked participants what would be required to reach the level of realism they would expect, participants' comments included "adding tactile stimulation to my hands", "larger field of view", and "finer EMS motions for the marble game".

Discussion of our findings

Our study results support our hypothesis, i.e., *EMS* did indeed significantly add realism to the three Mixed Reality tasks. And, for two of the three tasks, EMS had also significantly increased participants' enjoyment. These findings are further supported by participants' generally positive comments including "I like touching these real things [pointing at the book on the table]", which is the essence of why we used EMS to implement this functionality while keeping the users hands free.

At first glance, our findings are aligned with EMS research in VR [41, 37]. However, we also observed that, unlike in VR, exaggerated haptic effects (e.g., the impact of the ball when falling on the tray was bigger than of a ball that size) fall short of illuding the user in MR. As P3 noted "but this marble that I see cannot possibly be that heavy, I can see the world around me, so I can imagine the weights [of things]". In fact, P3 was pointing out a core quality of MR, which arguably makes it different from VR. In MR, experiences take place in the context of the physical world and thus users have a keener sense for plausibility. In the case of MR, we observed users remarking how they enjoyed nuanced aspects of the EMS-enabled physics, for instance: "I can feel the couch is harder to move when it is stopped [due to our EMS-based static friction]" (P3). As a recommendation for UX designers working in MR, we suggest aligning the "haptic-physics" with the expected physics as much as possible rather than resorting to exaggerations.

Lastly, it is worth noting that our study is limited in that it deals with the realism of the EMS haptic effects in MR games; hence, we asked users to freely explore the task at hand. Hence, these findings cannot be generalized for other tasks that require a measure of performance or precision.

CONCLUSIONS AND OUTLOOK

We demonstrated a fully mobile system that empowers Mixed Reality games and experiences with mid-air force feedback by means of electrical muscle stimulation. Our system, built around the HoloLens headset, and actuates the users' wrists, biceps, triceps and shoulder muscles. The main benefit of our approach is that it leaves users' hands free, thus allowing users to interact unencumbered—not only with virtual objects, but also with *physical* objects in their surroundings, such as props and appliances.

EMS opens novel interaction opportunities in MR

Besides the direct implications for increased realism in MR gaming, EMS might uncover new terrains for augmented passive objects and appliances. For instance, an appliance that is augmented with EMS might have more potential if we think of using it daily. Unlike *RetroFab* [52] that complements the appliance with updated hardware UI, an EMS-augmented appliance allows updating the UI of a device by merely updating the *software* (i.e., the EMS side).

Also, our tangible dial that automatically recalled the last position, i.e., the cup in the "walkthrough", points to another strength of exploring EMS in MR. EMS might assist in aligning virtual and physical realities to prevent inconsistent states often introduced by physical props (as debated in [33,28]). While previous methods solved this by mechanically coupling or actuating the props (e.g., mechanically constrained tangible dials [28]), EMS allows for everyday handheld objects to move without instrumentation.

Future work

We see this research as a first step towards more physical Mixed Realities by adding force feedback. The next steps might include combining this approach with tactile feedback, especially techniques such as back-of-the-nail vibrotactile [1, 2], which does not occlude the fingertips. Also, it might be worth exploring whether there are beneficial gains in task performance due to the haptic feedback.

Lastly, in our experiments we observed several shortcomings of the current state of EMS-based actuation, such as long calibration sessions for each user or the effect of unexpected users' postures on the desired output gestures. Thus, to maximize the potential of EMS-based haptics in Mixed Reality, researchers might consider tackling the following technical challenges: (1) simplification or automation of electrode placement, (2) including calibration routines that users can invoke in runtime, (3) increasing the system's robustness to variations in body posture and muscular fatigue, and (4) designing control loops that distinguish between induced and voluntary muscle contractions.

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