SaVR: Increasing Safety in Virtual Reality Environments via Electrical Muscle Stimulation

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ABSTRACT

One of the main benefits of interactive Virtual Reality (VR) applications is that they provide a high sense of immersion. As a result, users lose their sense of real-world space which makes them vulnerable to collisions with real-world objects. In this work, we propose a novel approach to prevent such collisions using Electrical Muscle Stimulation (EMS). EMS actively prevents the movement that would result in a collision by actuating the antagonist muscle. We report on a user study comparing our approach to the commonly used feedback modalities: audio, visual, and vibro-tactile. Our results show that EMS is a promising modality for restraining user movement and, at the same time, rated best in terms of user experience.

Figure 1: SaVR uses Electrical Muscle Stimulation (EMS) to prevent users from hitting physical obstacles while experiencing Virtual Reality (VR) applications. EMS actuates muscles resulting in an automated movement that pulls the arms away from a physical obstacle and thus increases the safety of the user.

CCS CONCEPTS

• **Human-centered computing** → **Human computer interaction (HCI)**; **Virtual reality**.

KEYWORDS

Virtual Reality; Safety; Electrical Muscle Stimulation; Feedback

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1 INTRODUCTION

In the last decade, Virtual Reality (VR) has moved from niche to mainstream. Recent technological advancements in VR headsets offer users an immersive open experience, even in narrow places (e.g., in living rooms). This sense of immersion is created mainly by addressing the users' vision, shifting their focus only to the virtual environment, and obstructing their perception of the surrounding real-world environment [30].

While the range of motion and immersion in the virtual scene continuously increases, perception of the real world further diminishes. However, loss of this perception can result in serious danger and injuries for users since they lose spatial knowledge and are thus unaware of obstacles such as furniture and walls. To our knowledge, little research has been conducted to investigate means for preventing these incidents and ameliorating safety in interactive VR environments. While systems that communicate boundaries to users exist (e.g., Oculus guardian system[1] and HTC Vive Chaperone[2]), the immersive experience can result in users not taking notice of systems' feedback.

To tackle this problem, we present SaVR, a wearable Electrical Muscle Stimulation (EMS) system, for increasing users' safety in VR. In contrast to visual and vibro-tactile feedback, EMS actively prevents the movement that would result in a collision with a real-world object by actuating the antagonist muscle to the user's movement. Thus, our primary goal is to actively prevent the user from hitting any object in the real world rather than communicate its existence to the user. For example, when the user wants to reach forward to catch items in VR, SaVR actuates the biceps so that the arm moves immediately backward and does not hit the cupboard in front (cf., Figure 1).

1.1 Contribution

The contribution of this work is two-fold. First, we present SaVR, an EMS feedback system that protects the user in VR environments by controlling the arm movement. Second, we report on a user study with twelve participants, comparing SaVR to the commonly used feedback modalities (i.e., vibro-tactile, audio, and visual). Our results show that EMS was the best in allowing the least overshooting out of the safe area. Additionally, it was the first-rated condition concerning the users' experience.

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[1] https://nyko.com/collections/products/products/vr-guardian
[2] https://www.vrheads.com/how-customize-htc-vives-chaperone-steamvr

2 RELATED WORK

VR applications aim to provide an immersive virtual environment to the user. One approach to achieve a high immersion is to increase the haptic experience of users in the virtual world through, for example, a new controller [27], dynamic passive haptics [32] or flying feedback devices [8]. Others opted to improve the most common feedback modalities, namely, vibro-tactile, visual, and audio [14]. For instance, Rietzler et al. combined tactile haptics and visual manipulations to enhance kinesthetics in VR environments [22]. Furthermore, VR decreases the users' awareness of the real environment (i.e., bystanders or obstacles). Therefore, another research direction focuses on communicating information on the real environment either by providing notifications to the user [18, 31] or by integrating existing real environment objects in the VR [9]. These methods, however, reduce the immersion of the VR scene.

With the rise of new technologies, Electrical Muscle Stimulation (EMS) became widely investigated [24]. Recent studies have been exploring the application of EMS in VR. Auda et al. used EMS to control the direction of the user's movement similar to the work of Pfeiffer et al. [20]. They created the illusion of moving in a straight line while the user moves in a circular path avoiding to bump into walls of the real environment [2]. EMS was further used, along with vibro-tactile, to communicate haptic feedback for different virtual objects [21]. Within the same scope, it was extended to induce haptic feedback in VR. Lopes et al. proposed a way to enhance immersion in VR scenes by creating a sense of repulsion and counter-force whenever the user tries to hold an object or hit a wall [12]. Further studies additionally explored the application for providing realistic impacts [11] or applying such a system in mixed reality [13]. In contrast to this, our work's goal is not to increase immersion by communicating haptics of virtual objects but to protect users of virtual reality systems from hitting obstacles in the real world.

3 THE SAVR APPROACH

We propose using Electrical Muscle Stimulation (EMS) as a new modality for increasing safety in Virtual Reality (VR) environments. Our approach has two main benefits. The first benefit is that it has a direct intervention on the body movement, ensuring the users' safety even in cases of high immersion and late reactions to warnings. The second benefit is that it does not interfere with the users' cognitive load, as it does not require any attention shift to the presented cues. That allows more attention to be on the actual task [1].

The concept of EMS is to directly influence the body motion using electrical impulses to elicit muscle contractions. These contractions lead to different motions, depending on the actuated muscle [16]. An external signal generator is used to generate the impulses, which passes the electrical signal to an electrode placed directly on the targeted muscle. EMS imitates humans' physiology, as in real life, the brain actuates our muscles by sending action potentials (i.e., electrical signals) generated from our nervous systems, causing different muscles to contract, and resulting in the corresponding body-part motion [16]. Previous research used EMS to control different movements of the body. Researchers actuated the arms empowering users to perform sign languages [6], or the hands allowing users to play an instrument [26]. Further, EMS has been used to actuate the legs to induce navigational commands [20] or correct gait [4, 28].

In this approach, we strive to protect the user from injury. One of the most common movements that might result in injury is when the user reaches out to an object in the virtual world. To prevent that movement, we actuate the antagonist muscle (i.e., the biceps).

4 EVALUATION

We conducted a study in a controlled lab environment to evaluate the SaVR approach, which is based on communicating feedback via EMS. We compared our approach to three other feedback stimuli: visual, auditory, and vibro-tactile feedback. We investigated the objective measurements of the logged data (i.e., tracked position of the participants' arm) and the participants' experience measured through the user experience questionnaire (UEQ) [7] and the presence questionnaire [29].

4.1 Application scenario

The suitability of the used feedback stimuli depends on the use-case [3]. Given that VR devices are nowadays mainly used for games, we implemented a game in Unity3D, in which, the participants' task was to catch falling balls. We placed a hidden hypothetical barrier 1500*mm* in front of the participants' starting position. This barrier mimics the real use case of having a physical obstacle (e.g., wall) that hinders users from moving freely. Thus, the participant could freely move within this 1500*mm* barrier but would receive feedback as soon as the barrier was crossed. We designed the participants' task so that 20 balls fall at a random position in front of the barrier, and 10 balls fall behind it. Consequently, participants would be forced to move around and stretch their arms, trying to catch the falling balls, and for some crossing the safety barrier.

4.2 Study Apparatus

We used an Oculus Rift to display the VR application. We tracked the users' hands using a Leap motion mounted directly on the Oculus Rift and visualized it to increase the sense of immersion [25]. We conducted the study in a 4m by 4m tracking space. Our main measure is the movement of the participants' hands outside of the safe zone (i.e., beyond 1500*mm* from the participants' starting point). For that, we needed to track their hand position with respect to the real world when they were reaching for the balls. As soon as a participant's hand reached the barrier, we communicated the feedback to them. To compare our approach to the state of the art, we developed three other types of feedback (i.e., vibro-tactile, visual, and auditory).

4.2.1 Vibro-tactile stimuli. For the vibro-tactile stimuli, we developed two wristbands using a battery-powered NodeMCU microcontroller and a disk vibration motor for each. We placed the vibration motor on top of the wrist of the participant as is done with the Nyko VR Guardian system. Once the activation trigger is received, the wrist bands keep vibrating until the trigger is deactivated (i.e., the user moves his arms back to the safe area).

4.2.2 Visual stimuli. For visual feedback, we implemented a translucent blue wall at the location of the barrier. We designed the barrier similar to that of the guardian system of the Oculus Rift. This feedback appeared as soon as the participant reached the barrier.

4.2.3 Auditory stimuli. The auditory feedback stimuli were in the form of a beep similar to those of parking assistants in cars. As soon as the participant moved a hand through the virtual barrier, a beep sound was played.

4.3 Study Design

In this study, we used a within-subject design. The overall goal is to compare the different feedback modalities (i.e., *EMS*, *Visual*, *Audio*, *Vibro-tactile*) with one another. Thus, the feedback modality is the independent variable. As dependent variables, we assessed the performance of the participants (i.e., reaction time, over-crossed distance), as well as their user experience and presence.

4.4 Participants and Procedure

We invited 12 participants (3 female, 9 male) aged between 19 and 33 years ($M = 25.75$, $SD = 4.59$) to our lab. The study took place in a quiet room without any other sources of noise. First, the participants filled out consent forms and read the study description. In addition, we verbally explained the study to ensure that the participants were aware of the different stimuli used. In particular, we made them aware of the safety restrictions of the off-the-shelf EMS we used. Next, we equipped the user with the EMS device and the vibro-tactile wristbands. We attached two self-adhesive electrodes on each bicep muscle of each arm (cf., Figure 1). The contraction of these muscles would result in the arm's pull-back motion. Next, we calibrated the EMS device using the *let-your-body-move* toolkit [19]. At the beginning of the EMS trial of each participant, using signal generator, we adjusted the generated intensity to actuate the targeted muscle (i.e., biceps). As the actuating signal intensity differed from one person to the next as well as from one arm to the other, we started with a base signal of 5 micro Ampere and used a step-increase with the same value. We stopped when the actuation resulted in pulling the arm upwards. We also indicated the sequence of the displayed modalities. Then, without using any feedback modalities, we provided a 1min trial, just to familiarize the users with the task. After the introduction, we presented each of the four conditions to the user in a counterbalanced order using a Latin square design. Every participant played the game with each of the four stimuli for around 2 $minutes$ each. Throughout the user study, one researcher made sure that participants did not bump into a wall. After every stimulus, the participant filled in the UEQ and the presence questionnaire to assess user experience and presence.

5 RESULTS

For the evaluation of our system, we first measured the device-related delay for each of the modalities. Based on the observed delay, we analyzed our recorded data. We then examined users' experience and presence with the user experience and presence questionnaires, respectively.

Delay measurement. In our study, we compared four modalities, relying on different devices to communicate the feedback to the participant. Since we measured reaction time and had two modalities using a wired connection (*Audio*, *Visual*), and two modalities using a wireless connection (*vibro-tactile*, *EMS*), it was necessary to take the delay induced by each device into consideration. To measure the delay, we implemented a simple UI in Unity3D (our main application), consisting of one button for each condition. Then, we used a camera to record the button press in the UI, and the response from the feedback inducing device. For *Vibro-tactile* and *EMS*, we had to additionally use an oscilloscope to visualize the electrical activity and capture it with the camera. For example, for *EMS*, we connected two oscilloscope probes, one to each end of the *EMS* pads. In total, we took nine measures for each modality (one per minute). In line with previous work [5], we found the mean delay to be *85 ms* for *visual*, while we did not find a delay for *Audio* (likely because no rendering factor caused any delay). For *Vibro-tactile*, we measured a mean delay of *200ms*, and for *EMS*, we measured a mean delay of *390ms*. For *EMS*, we assume that the larger delay results from the used modulation device (to generate the EMS signal, cf., [19]), which adds further delay to the wireless connection [15].

5.1 Reaction Time

We also investigated the reaction time in each of the modalities. That is the mean time taken by the participants from the moment they receive the feedback to the first moment in which they start to withdraw their arm.

The results show that the participants were fastest in the *Vibro-tactile* condition ($M = 1085ms$), followed by *EMS* ($M = 1307ms$), then *Visual* ($M = 1336ms$), and finally *Audio* ($M = 1840ms$). A Shapiro-Wilk-Test showed that our data is not normally distributed ($p < 0.001$), and thereafter we ran a Friedman test that showed no significant effect across the four modalities ($\chi^2(3) = 4.5, p = 0.212, N = 12$).

5.2 Over-crossed Distance

Next, we inspected the maximum over-crossed distance across the four conditions. That is the distance crossed from the time the participants received the feedback until the first moment when they pulled their arms backward.

The results show that the best-recorded performance was in *EMS* ($M \approx 200mm$), followed by *Vibro-tactile* ($M \approx 238mm$) then *Audio* ($M \approx 325mm$), keeping the *Visual* feedback ($M \approx 338mm$) with the highest over-crossed distance (cf., Figure 2). A Shapiro-Wilk-Test showed that our data is not normally distributed ($p = 0.036$), and thereafter we ran a Friedman test that revealed a significant effect across the four modalities ($\chi^2(3) = 11.9, p = 0.008, N = 12$). A post-hoc test using Wilcoxon Signed-rank with Bonferroni-Holm correction showed significant differences between the *Audio* and *EMS* conditions ($V = 4.0$, $p = 0.03$, $r = 0.77$), as well as the *EMS* and *Visual* conditions ($V = 2.0$, $p = 0.02$, $r = 0.19$).

5.3 User Experience Questionnaire

Looking at the results of the User Experience Questionnaire [10], the overall user experience is highest for the *EMS* condition ($MD = 1.68$, $IQR = 0.62$) followed by *Audio* ($MD = 1.12$, $IQR = 1.09$) and *Vibro-tactile* ($MD = 0.87$, $IQR = 0.56$). The *Visual* condition received the overall lowest ratings ($MD = 0.81$, $IQR = 1.46$) (cf., Figure 3). We ran a Friedman test that revealed a significant effect across the four modalities ($\chi^2(3) = 9.18, p = 0.0269, N = 12$).

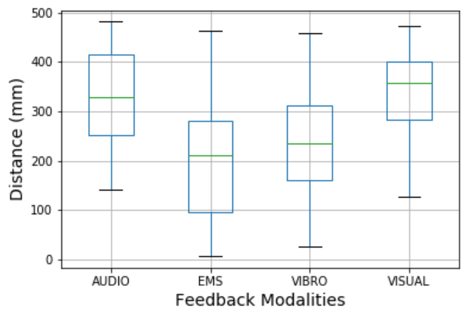

Figure 2: The maximum distance over-crossing the hypothetical barrier across the four feedback modalities

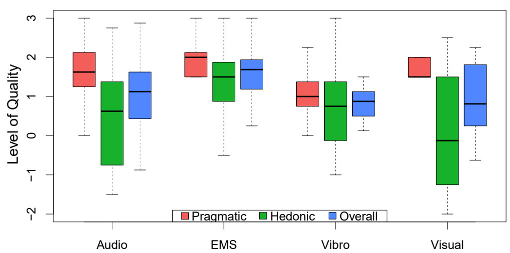

Figure 3: User experience questionnaire results. This shows the comparison between the four tested conditions overall and across both the hedonic and pragmatic evaluation.

Further analysis into the pragmatic qualities show that *EMS* ($MD = 2$, $IQR = 0.5$) and *Audio* ($MD = 1.62$, $IQR = 0.8$) have the best scores followed by *Visual* ($MD = 1.5$, $IQR = 0.5$). *Vibro-tactile* had the worst score among the four conditions ($MD = 1$, $IQR = 0.43$). A Friedman test showed statistically significant difference in the scored pragmatic qualities across the four conditions ($\chi^2(3) = 11.97, p = 0.007, N = 12$). However, no statistically significant difference was observed from post-hoc tests.

In addition, the hedonic qualities show that *EMS* ($MD = 1.5$, $IQR = 0.75$) has the best score followed by *Audio* ($MD = 0.62, IQR = 1.93$) and then *Vibro-tactile* ($MD = 0.5$, $IQR = 1.18$). The *visual* condition in this case had the worst score among the four conditions ($MD = -0.12$, $IQR = 2.62$). A Friedman test showed a statistically significant difference in the scored pragmatic qualities across the four conditions ($\chi^2(3) = 8.77, p = 0.032, N = 12$). However, no statistically significant difference was observed from post-hoc tests.

5.4 Presence Questionnaire

The results of the presence questionnaire show similar results for each condition except for the quality of interface sub-scale (cf., Figure 4). Here, visual feedback was rated as worse than the other conditions. However, Friedman tests could not show any statistically significant differences, each ($\chi^2(3) = 4.56, p = 0.2, N = 12$).

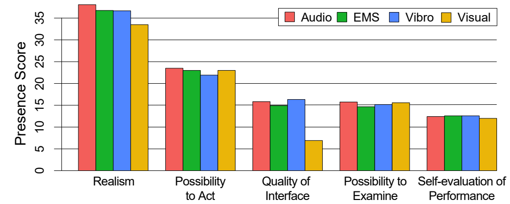

Figure 4: Presence questionnaire results. They show the comparison between the four tested conditions in each of the dimensions of the questionnaire.

6 DISCUSSION

Modality. Previous literature shows that tactile feedback has the shortest reaction time when compared to visual and audio feedback [17]. That was also confirmed in our study, where the participants reacted fastest to the *Vibro-tactile* stimuli followed by *EMS*. In a VR game, both the auditory and visual channels might already be overloaded [23]. Given this, it is better to use a different channel to prevent the user from missing the feedback, as our results indicate may happen.

User Experience and Immersion. In general, the gathered data generated promising results. The results of the user experience questionnaire show that users have a high acceptance level of *EMS*, as they rated the hedonic quality of *EMS* highest. That was also reflected by the pragmatic quality, since *EMS* has the second highest rating, after the *Visual* condition. However, the *Visual* condition has the drawback that it reduces the immersion considerably by altering the visuals. Also, we highlight the fact that *EMS* has a different nature than the other stimuli. *Visual*, *Audio*, and *Vibro-tactile* require a different amount of attention and induce various cognitive loads which might further negatively impact the user experience.

Application Scenarios. In this work, we explored a simple grasping scenario. Besides grasping several other movements might result in injury. We used *EMS* to actuate the biceps to prevent the user from grasping further. Related work shows that other muscles could also be actuated to either prevent the user from walking into obstacles [2] or kicking them [11].

Limitation. We acknowledge the following limitation of our work. We designed an interactive virtual reality scene to provoke the user to actively move and, consequently, have a high sense of immersion without paying attention to the real physical world. The falling balls were good for that purpose, yet, the balls fell in one direction (i.e., in front of the user). Therefore, the user did not experience moving in a different direction (i.e., rotating). This affected the kinesthetic motion learning curve. Furthermore, the scene provided only visual stimuli. This is slightly different from current VR games which typically provide auditory feedback as well.

7 CONCLUSION

We presented SaVR, an Electrical Muscle Stimulation (EMS) system that increases user safety in Virtual Reality (VR) environments in which the users' spatial knowledge is limited only to information provided by the VR environment. The concept of EMS is to induce an electrical signal on a targeted muscle to actively pull it away from hitting any obstacle in the real world. While there are several stimuli to communicate warnings to users in VR (e.g., visual, auditory, and vibro-tactile), none of them influence the user's actions without requiring additional attentional shift and increasing cognitive load. We implemented our system and evaluated its performance with 12 participants by comparing the results with the most known feedback stimuli (i.e., *Audio*, *Visual*, and *Vibro-tactile*). We demonstrated that SaVR provides the best secure performance and results in the best user experience.

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