Around the (Virtual) World

Infinite Walking in Virtual Reality Using Electrical Muscle Stimulation

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ABSTRACT

Virtual worlds are infinite environments in which the user can move around freely. When shifting from controller-based movement to regular walking as an input, the limitation of the real world also limits the virtual world. Tackling this challenge, we propose the use of electrical muscle stimulation to limit the necessary real-world space to create an unlimited walking experience. We thereby actuate the users' legs in a way that they deviate from their straight route and thus, walk in circles in the real world while still walking straight in the virtual world. We report on a study comparing this approach to vision shift – the state of the art approach – as well as combining both approaches. The results show that particularly combining both approaches yield high potential to create an infinite walking experience.

CCS CONCEPTS

• **Human-centered computing → Virtual reality**;

KEYWORDS

Virtual Reality; Electrical Muscle Stimulation; Walking; Locomotion

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Figure 1: Left, the user walking in VR on a straight path. Right, the user's leg is rotated via EMS to the left. Now the user walks on a circle. (Staged scene)

1 INTRODUCTION

Natural motion like walking in Virtual Reality (VR) has the potential to foster the immersion of the user [20]. One key challenge is fitting a possible infinite virtual space into a limited real environment such as a living room. Previous work focused on letting the user move differently in the virtual world than he/she moved in the real environment [20–22]. Concepts like shifting the user's view were introduced to guide the user on a physical path that differs from the virtual world [2, 22]. To explore large virtual spaces by natural body motion other approaches compressed them into smaller physical spaces by overlapping virtual spaces [23]. These approaches require a certain room size which is normally not available in regular households (e.g., $40m \times 40m$ [21]). Thus, further research is needed to further decrease the spatial requirements.

In this paper, we combine vision shifting techniques with Electric Muscle Stimulation (EMS) to further decrease the physical space needed to walk endlessly in VR. Different research projects showed ways to control the user's walking with EMS in the real world. Either EMS changes the direction in which a user is walking [17] or the legs are adjusted to a healthier posture [5]. Building upon that work, we built a system that actuates the muscles in a way that the movement of the user in the virtual world is decoupled from the movement in the real world. This allows the user to infinitely walk in the virtual world without the necessity to have an infinite physical world.

The contribution of this work is twofold. First, we report on the design and implementation of our infinite walker system using EMS actuation to provide an infinite walking experience in VR. Second, we report on a user study in which we evaluated the system. Therefore, we combined EMS with the vision shift approach. We show that particularly the combination of shifting the vision and EMS outperforms both individual approaches, allowing users to walk in circles with an average radius of $5.48m$.

2 RELATED WORK

In this paper, we draw upon two strands of related work. First, we review approaches which allow users to move freely in virtual realities. Second, we present work that exploits muscles actuation for interactive systems.

Moving in Virtual Reality

Different approaches exist that support users moving around in virtual reality. In contrast to approaches like walking in place [24] or teleportation [4], our approach focuses on natural walking. As space is a big limitation for walking around freely, different approaches were explored to tackle the issue. One approach is vision shift. Vision shift is a concept that manipulates the user's view by a certain number of degrees [2]. As a result, as soon as the users compensate for that i.e. following the shifted view, they start to slightly redirect their walking direction. This technique of redirected walking enables natural locomotion through a virtual environment that is considerably larger than the available real-world walking space. In general, vision shift plans a walking path through a virtual environment and calculates the parameters for combining translation, rotation, and curvature gains of the walking redirection. This is done to rotate the user's orientation away from the boundaries of the physical space. In this context, Suma et al. found that subtle techniques for continuous or discrete reorientation implicates fewer reported breaks in presence by the participants, if the technique was applied optimally [22]. Ideally, the user would not notice redirection techniques, so that the virtual reality implementation remains as immersive as possible.

To use limited physical space for relatively large virtual spaces "*Impossible Spaces*" was introduced [23]. Suma et al. explored how virtual spaces can be overlapping to be able to fit into a smaller physical space. They showed that small virtual rooms ($3.66m \times 7.32m$) can overlap by 56% until users recognized the overlapping and for larger virtual rooms ($9.14m \times 9.14m$) up to 31%. Conversely, other techniques/concepts used for creating infinite walking experiences used active re-positioning such as treadmills, motorized floor tiles, and human-sized hamster balls [12, 14].

Further approaches for navigating through VR are presented such as arm swings [15]. *ArmSwing* controls the movement of a user by the swing of their arms. The system navigates in the direction where the arms are swung, without any feet or head movement. Moreover, Agethen et al. analyzed the behavior of human locomotion in the real world and VR for the manufacturing industry and found clear trend participants reduce their walking speed and acceleration in VR (up to 13 %) [1]. Besides of walking in a flat world Schmidt et al. and Nagao et al. conducted research in the area of stepping and walking on barriers and stairs [13, 18].

Electrical Muscle Stimulation

Electrical Muscle Stimulation (EMS) has recently received an increased amount of attention from the HCI community [19]. EMS delivers a weak electrical signal to the muscles. The electrical signal elicits action potentials on motor nerves, which control muscle fibers. Stimulating these motor nerves leads to contraction of the muscle fibers.

EMS has been used in several applications such as supporting the user while drawing graphs [11], communicating the affordance of objects [10], or sharing the emotions with a remote partner [6].

Additionally, EMS has been used to augment user's walking. Pfeiffer et al. showed the feasibility of manipulating the direction of a walking pedestrian by using non-invasive electrical muscle stimulation [17]. Two self-adhesive electrodes were attached to the participant's sartorius muscle. Other muscles of the human leg are inaccessible for electrode pads, because they are deeply embedded in tissue, or are partially located in intimate zones of the body. Contraction of the sartorius leads to flexion of the hip and the knee joints. Based on their results of a possible direction change of a human leg up to an average of 15.9°/m, we are developing a system for a slight change of the direction the human is not recognizing. In the *FootStriker* project, Hassan et al. and Wiehr et al. also researched in the area of locomotion combined with EMS [5, 25]. They provide corrections to the user's gait while running.

To foster immersion in VR, EMS has been used to provide haptic feedback. Lopes et al. realized different virtual objects using EMS feedback [9]. Particularly, the system was evaluated to increase realism in VR scenarios by providing impact experience to its users.

3 ACTUATED WALKING

The main idea of this work is to use electrical muscle stimulation to create the experience of an unlimited walking in virtual reality. While current methods either use room-sized setups (e.g., Cakmak and Hager [3]) or modify the visual experiences (e.g., vision shift [21]), we propose a partly on-body system that actuates the legs of the user. In particular, we slightly twist the legs outwards by actuating the *sartorius muscle* so that the user does not noticeably walk in circles instead of straight similar to the work of Pfeiffer et al. [17]. This actuation is realized with one pair of electrodes per leg.

System

Our system consists of the following components depicted in Figure 2: an *EMS Control Unit*, a *Step Detector*, a *user tracking system* (cf., Figure 4), and a *VR scene* (cf., Figure 3).

Figure 2: The *Infinite Walking* setup including cameras and markers for tracking, EMS Control Unit and Electrodes for actuating, Step Detector for properly timed actuation, and Oculus GO for displaying the VR scene. (Staged scene)

Figure 3: VR scene with trees. This scene is shown on the *Oculus Go.* Movement of the real world is transformed to either forward or backward movement in VR.

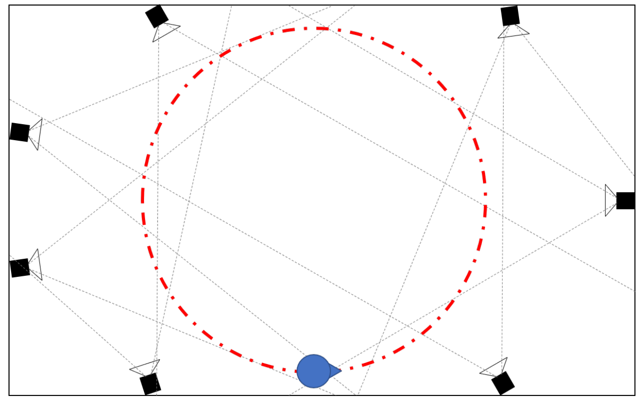


Figure 4: Overview of the *Infinite Walking* setup including cameras, ideal walking path (red) and participant (blue).

Step Detector

To properly apply electric muscle stimulation (EMS) we had to detect when the user lifts his/her left leg. Therefore we developed the *Step Detector*. We used a *Interlink FSR 400 Short* force sensor which is placed underneath the left shoe (cf., Figure 2, *Step Detector*). We connected it to a *Arduino Pro Mini* and *SparkFun Bluetooth Mate Gold* board. The board is connected wireless via Bluetooth to a smartphone (i.e., *Samsung Galaxy S7*). The *Step Detector* sends an actuation command to the *EMS Module* as soon as the leg of the user is in the air, in order to actuate the muscle, thus, the leg is turned outwards. As soon as the leg hits the ground, the Step Detector sends a stop signal. There is no significant delay between step detection and triggering EMS.

EMS Control Unit

To actuate the leg of the user we have built an *EMS Control Unit* (cf. Figure 2, *EMS Control Unit*). We used a *STIM-PRO T-800* electric muscle stimulation device and the Let-Your-Body-Move toolkit [16] of Pfeiffer et al. as the *EMS Control Unit*. The device is connected via Bluetooth to a smartphone (i.e., the same *Samsung Galaxy S7* as used by the *Step Detector*). When the *Step Detector* sends an activation signal to the smartphone the *EMS Control Unit* actuates the leg. Meaning, the electrical current is sent through two self-adhesive electrodes that we attached to the *sartorious muscle* (cf., Figure 5) of the user. That leads to an outwards rotation (cf., Figure 1, right).

User Tracking

To track the user and to transfer real-world motion into VR we used seven *OptiTrack Prime 13* infrared cameras (cf., Figure 2, *OptiTrack Camera*) and *19 mm (3/4") M4 Markers* (cf., Figure 2, *OptiTrack Marker*) in a certain arrangement to track the user in the entire tracking area (cf., Figure 4). We took an off-the-shelf backpack and attached a rigid body consisting of markers to track the position and orientation of the user. We used the X-, Z- coordinates to track the position. The X-axis and Z-axis built up the ground plane in most computer games. Furthermore, we used the rotation around the Y-Axis as the body orientation of the user. The position and rotation data is streamed by a tracking server to the *Oculus Go* (cf., Figure 2, *Oculus Go*) which runs the VR application (cf., Figure 3).

Virtual Reality Application

For the purpose of evaluation, we developed a VR application that lets the user walk a path between two rows of trees using Unity3D (cf., Figure 3). The user can only move forward or back, not sideways. When the user turns his/her head he/she can freely look in every direction while walking. When the user was walking in the real world, the position data was streamed by the tracking server to the VR application over WiFi. The position data is used to calculate how much a user has moved forward to apply this translation to the position in the virtual environment. The circular movement of the user in the real world was transformed into a linear movement in VR. Because a turn in the real world would lead to a turn in the virtual environment we used the body orientation to re-adjust the viewing angle of the user. The rotation of the user in the real world is subtracted from the viewing rotation in the virtual world. This is necessary, otherwise, the user could not walk straight in VR when he/she is, in fact, walking in a circle in the real world. Because the *Oculus Go* has built-in sensors that enable the user to look around, he/she can still normally look around in VR, but the overall rotation of the user in the virtual world remains the same all the time.

4 EVALUATION

To evaluate our system we conducted a user study comparing the *EMS* approach to the vision shift approach, as well as, a combination of both (EMS and vision shift). In the *EMS* condition, we used the aforementioned system and actuated the left leg of the participant to make him/her rotate to the left while walking. In the *shift* condition we shifted the view of the participants always to the left to make them walk in a circle. We applied a shift of the vision with an angle of 8° to the left. This results in an arc that fits into the study room following the findings of Steinicke et al. [21]. Using the taxonomy from Suma et al., this redirection technique can be classified as a subtle, continuous reorientation [22]. In the last condition, we applied both – shifting the view of the participant and actuating his/her left leg.

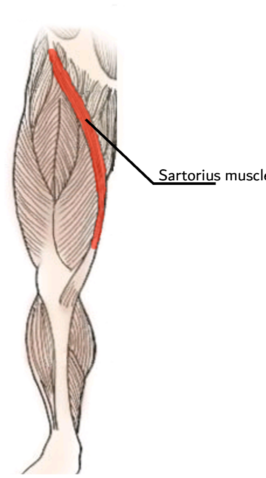


Figure 5: We use the sartorius muscle which is the longest muscle in the human body. This muscle rotates the leg outwards.

Study Setup

We conducted the study in an empty room with a tracking space of approx. 8 x 8 meters. We tracked the user's movement with a *OptiTrack Prime 13* tracking system through markers attached to the backpack of the participants (cf., Figure 2).

Participant and Procedure

We invited 12 participants to take part in our study (10 male, 2 female, aged between 20 and 32 years ($M = 25.92, SD = 3.55$)). All participants were either students or employees of the university. First, we informed each participant about the procedure of the study both with written material and personal instruction. In particular, we ensured that every participant met the personal requirements of using an EMS device, such as not being subject to high fever, having cardiac arrhythmia, or other heart conditions [19]. The participants ensured that they understood the procedure by signing a consent form.

We attached electrodes to the *sartorius muscle (musculus sartorius)* (cf. Figure 5). For each participant, we individually calibrated the *EMS* signal to get the highest muscle actuation, while not inducing pain or discomfort to the participant.

After the preparation, each participant walked in each condition (*Shift*, *EMS*, and *Shift + EMS*) for 5 minutes in VR. The three walking conditions were counterbalanced using Latin square. Throughout the whole study, an experimenter made sure that the participants do not collide with any object within the room, such as walls. After walking for 5 minutes in one condition, we asked the participants to stop walking and to fill out the *User Experience Questionnaire* [8] and the

Participant	Shift		EMS		Shift + EMS	
P1	14.98	11.40	11.57	10.39	7.65	7.85
P2	3.49	5.22	12.13	12.11	4.52	4.09
P3	1.37	1.19	1.53	3.92	1.24	1.16
P4	3.90	3.73	10.26	12.65	5.99	6.55
P5	1.64	1.17	2.87	3.05	1.54	1.68
P6	2.22	3.37	11.28	11.34	1.39	0.35
P7	3.02	3.52	6.66	8.87	1.34	0.55
P8	11.12	10.31	12.61	11.84	11.05	9.46
P9	17.07	11.95	15.42	12.88	16.50	10.13
P10	0.46	0.16	3.80	5.20	0.59	1.69
P11	7.22	7.94	8.45	10.97	5.88	7.56
P12	9.89	10.22	7.86	9.28	8.03	7.44
Mean	6.37	5.39	8.70	4.12	5.48	4.62

Table 1: Average (and SD) radius (in m) for each participant in each condition.

Simulator Sickness Questionnaire [7]. Then, the next condition was tested. After each participant walked in each condition we conducted an interview.

Results

In the following, we present the results of the study.

Data Preparation. Since we captured movement data of each participant, we first prepared the data for further analysis. In a first step, we smoothed the recorded data. Due to the fact that we attached the markers of the tracking system to a backpack, the markers were shaking while the participants were walking. To properly analyze the data we smoothed the data by applying a sliding window mean filter. Since participants sometimes reached the boundaries of our tracking system, we stopped them and manually turned them around. We excluded these turns from our data-set resulting in a participant's path that is divided into several slices. For each slice, we fitted a circle into every 100 samples of the recorded data. We chose 100 samples because the sampling rate of the tracking system was 100 Hz. Hence, we chose a one-second interval, in order to properly remove the wobbling and calculate the circle without changing the overall appearance of the movement, since it is about the time needed for 1-2 steps. In case that there are less than 100 samples left, we did not further consider this data for further analysis. Lastly, we calculated the mean radius by overall fitted circles per user per condition.

Movement Radii

In a first step, we compared the different movement radii of the three conditions (cf., Table 1). The results show that *Shift + EMS* ($M = 5.48m$, $SD = 4.62$) outperformed *EMS* ($M = 8.70m$, $SD = 4.12$) and *Shift* ($M = 6.37m$, $SD = 5.39$) applied individually. A repeated measures analysis of variance (ANOVA) reveals statistically significant differences, $F(2, 22) = 6.223, p = .007$. Follow up Bonferroni-corrected post-hoc tests show that *Shift + EMS* results in statistically significant smaller radii compared to *EMS*, $t(11) = 3.456, p = .015$. All other comparisons could not reveal statistically significant differences. In Figure 6, we plotted the walking paths for one participant (P8) for all three conditions (*Shift*: left, *EMS*: middle, *Shift + EMS*: right).

User Experience

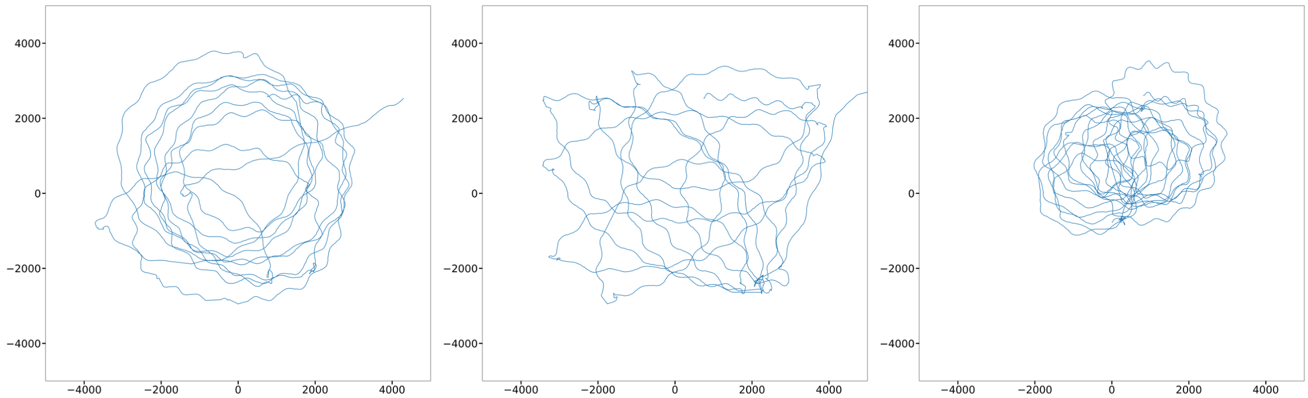
Looking at the results of the User Experience Questionnaire, the overall user experience is highest for the *Shift + EMS* condition ($M = 1.25$, $SD = 1.06$) followed by *EMS* ($M = 1.24$, $SD = 0.93$). The *Shift* condition received the overall lowest ratings ($M = 0.96$, $SD = 0.98$). A Friedman test could not show statistically differences between these conditions, $\chi^2(2) = 1.756$, $p = .416$. Looking at the hedonic quality, *Shift + EMS* ($M = 1.54$, $SD = 1.30$) outperformed both, *EMS* ($M = 1.22$, $SD = 1.56$) and *Shift* ($M = 0.98$, $SD = 1.55$). A Friedman test showed statistically significant differences between these conditions, $\chi^2(2) = 6.513, p = .039$. Post-hoc Bonferroni-corrected Wilcoxon Signed Ranks tests showed that *Shift + EMS* was rated statistically significantly better than *Shift*, $Z = 2.448, p = .042$. All other comparisons could not show any statistically significant differences ($p > .05$). For the pragmatic quality, *EMS* performed better ($M = 1.25$, $SD = 0.83$) compared to *Shift + EMS* ($M = 0.96$, $SD = 1.10$) and *Shift* ($M = 0.94$, $SD = 1.02$). Using a Friedman test, we could not show any statistically significant differences, $\chi^2(2) = 0.439, p = .803$.

Simulator Sickness

The simulator sickness questionnaire explores oculomotor and nausea. For nausea, the *Shift* condition performs worst ($M = 2.08$, $SD = 2.15$) followed by *Shift + EMS* ($M = 1.83$, $SD = 2.79$). The *EMS* condition performed best ($M = 1.50$, $SD = 1.31$). A Friedman test could not show any statistically significant differences, $\chi^2(2) = 1.000, p = .607$. The results of the oculo-motor sickness part also show that *Shift* performs worst ($M = 3.75$, $SD = 2.63$), followed by *Shift + EMS* ($M = 3.17, SD = 3.81$) and *EMS* ($M = 2.33, SD = 1.92$). A Friedman test could not show any statistically significant differences, $\chi^2(2) = 4.974, p = .083$.

Interview

We conducted semi-structured interviews after the participants finished walking in all three conditions. We asked the participants about their walking experience in VR and their general perception of the different conditions.



(a) P8, Vision Shift (b) P8, EMS (c) P8, Vision Shift + EMS

Figure 6: The walking paths of one exemplary participant (P8) in the *Vision Shift* (left), *EMS* (center), and *Vision Shift + EMS* (right) condition. The plotted area covers $10m \times 10m$.

Immersion. For the two conditions (*Shift* and *Shift + EMS*) in which the view was shifted 8 out of 12 participants said that they recognized the shift ("*I felt that the vision was shifted to the left.*" [P1]). Further, one commented that it "*felt unsafe and shaky with the vision shift*" [P8]. One participant also complained about the intensity of the vision shift by stating that "*the image shifted really strong - it was difficult to walk*" [P10]. In contrast, participants stated that they "*did not really feel the EMS*" [P8] and that "*walking with only EMS was pretty normal, straight, and easy to follow*" [P2].

Cognitive demand. For *Shift + EMS* 4 participants reported that they were supported best during walking and that the demanded focus on the walking path was lowest. "*While walking with shifted vision and EMS I recognized that I was walking in a circle because no one stopped me. It was less challenging than in the other conditions.*" [P6]. Participants also mentioned that "*EMS was supportive during walking*" [P3] and "*helped walking in a circle.*" [P4]. They further added that they "*had not to focus all the time while [. . .] walking.*" [P6]. This indicates that EMS induced a lower cognitive load. When the vision was shifted, more focus was demanded by the participants. "*Shifting the view was somehow disturbing because one had to adjust to the view and walk the circle. One had to focus on that*" [P6]. Adding EMS to the shift further helped to reduce focus demand "*With shift only, I had to focus to follow the path. I could never relax. With EMS I had not to focus that much. With shift and EMS I was not re-adjusted once*" [P7]. On the other hand, EMS can be disturbing or tedious. P7 stated that "*at the beginning EMS was a little bit unpleasant not painful but inconvenient. You know that it is triggered when you lift the leg. But it is still surprising.*" While P8 mentioned that "*walking [with EMS] became more and more uncomfortable because I got tired.*"

5 DISCUSSION

Further decreasing the physical space needed to walk infinite in VR is still one key challenge in developing highly immersive VR applications. With the combination of shifting the view of the user and actuating his/her leg during walking, we could successfully decrease the space needed for walking on a circle, which yields to an infinite walking experience in VR (cf., Figure 6). Although the difference seems not too impressive, it can make the difference if a VR system can be deployed in a certain area or not. For example, a room could be on average around $33m^2$ smaller for *Shift + EMS* ($\pi * (5.48m)^2 = 94.3m^2$) compared to only *Shift* ($\pi * (6.37m)^2 = 127.5m^2$) in the case of our setup.

Looking at the different average radii of each participant, we see variations in size. One reason is that not all users are responding the same way to the EMS signal, which is common in EMS studies (e.g., due to different muscle strength, skin thickness, etc.) Also, some participants reacted to the vision shift stronger than others. Some of them stated that they did not really recognize the shift, whereas others suspected that the vision is slightly shifted. P10, for example, stated in the interview that it was difficult to walk with the vision shift applied. Thus, P10 walked slowly and in a very small area resulting in small radii.

Participants stated that the focus demanded by walking in VR was lower when *EMS* was used in addition to *Shift*. Thus, several application scenarios could be defined. *EMS* could be dynamically applied on demand in respect to the virtual world e.g. guiding the user back to the middle of the room if he/she reaches its bounds.

Looking at the mean radii of all three conditions, the results show that the combination of *Shift* and *EMS* outperforms the two single approaches. This was also supported by the results of the UEQ. Comparing the EMS to the vision shift approach, the results were mixed. While the overall radius was lower for the *Shift* than for the *EMS*, participants mentioned throughout the interviews that shifting the vision was quite conspicuous. Thus, a more subtle vision shift would result in a larger average radius but also in higher user experience. Both approaches therefore are highly dependent on the chosen intensity. This implies for future VR walking systems that both approaches need to be adjusted to the available room size.

6 CONCLUSION AND FUTURE WORK

In this work, we explored a novel way of providing an infinite walking experience to users in virtual realities. We show that by applying electrical muscles stimulation to the *sartorius muscle*, we can actuate the leg in a way that the movement in the real world is decoupled from the movement in the virtual world. Thus, a user can walk straight in the virtual world but walks in circles in the real world. Comparing the results with a vision shift approach, as well as a combination of both, we found that the combination yields advantages for the user. While we focus on walking straight, future work could investigate how EMS can be used to enable users to freely walk in virtual reality. As soon as a user approaches an obstacle (e.g., a wall), EMS is actuating the user in a way that he or she starts walking a circle.

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