Electrical Head Actuation: Enabling Interactive Systems to Directly Manipulate Head Orientation

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Figure 1: (a) We propose a novel interface concept that enables interactive systems to directly actuate the user's head orientation around its yaw (i.e., left/right) and pitch (i.e., up/down) axis by applying electrical muscle stimulation (EMS) to the neck muscles. Actuating the neck muscles with EMS is uncharted territory for interactive systems, yet, enabling it opens up a range of applications not possible before: (b) directly changing the user's point-of-view to locate target objects in a fire safety training; (c) a sound controller that uses neck movements as both input and output; (d) transmitting one users' neck movement to another; and, (e) rendering force feedback from VR punches on the head. (f) Finally, we explored users' experience on our electrical head actuation.

ABSTRACT

We propose a novel interface concept in which interactive systems *directly* manipulate *the user's head orientation*. We implement this using electrical-muscle-stimulation (EMS) of the neck muscles, which turns the head around its yaw (left/right) and pitch (up/down) axis. As the first exploration of EMS for head actuation, we characterized which muscles can be robustly actuated. Second, we evaluated the accuracy of our system for actuating participants' head orientation towards static targets and trajectories. Third, we demonstrated how it enables interactions not possible before by building a range of applications, such as (1) synchronizing head orientations of two users, which enables a user to communicate head nods to another user while listening to music, and (2) directly changing the user's head orientation to locate objects in AR. Finally, in our second study, participants felt that our head actuation contributed positively to their experience in four distinct applications.

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CCS CONCEPTS

• **Hardware** → Emerging technologies.

KEYWORDS

Electrical Muscle Stimulation, Haptics, Augmented Reality, Virtual Reality

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1 INTRODUCTION

While head movements are integral in life and, in many interactive systems (e.g., scanning one's surroundings in VR/AR or as nonverbal cues in telepresence), researchers have rarely explored ways to directly utilize head movements as *output*. When it comes to haptic actuation, researchers predominately focus on actuating the user's hands [6, 59] arms [36, 45, 60], or feet [17, 48]. Even though actuating the limb's extremities has proven promising for guiding user's touch [6, 66], movements [35, 41] and even walking direction [48], very few interactive systems explored the potential of *directly actuating head movement.*

There have been four types of explorations in actuating the head: (1) emergent exoskeletons used only in medical rehabilitation [69]; (2) mounting a flywheel to the VR headset to render inertial

neck movements	muscles		
left/right (cervical rotation)	sternocleidomastoid (one side)	splenius cervicis (one side)	splenius capitis (one side)
up (cervical extension)	upper trapezius	splenius cervicis	splenius capitis
down (cervical flexion)	sternocleidomastoid	longus group (colli and capitis)	rectus capitis
left/right tilt (cervical lateral flexion)	scalenes	levator scapulae	

Figure 2: Main muscle groups that control the human neck, which we explored to understand how to robustly actuate the head with EMS (muscle names in gray denote deep muscles that are hard-to-reach with non-implanted EMS).

forces, which uses the gyroscopic effect as the user's head is actively moving [14]; (3) mechanically applying pressure to the head causing it to jerk in one direction, denoted as hanger reflex [27]; and (4) using air jets mounted to the VR headset to render accelerations of the head [32].

Unfortunately, while all the above haptic interfaces are promising, they are built around the assumption that one *can just attach actuators to a headset* or, even more dramatically, that *all users will be excited to attach actuators on their face, forehead, etc.* Thus, these are mostly limited to VR, where a headset is already present.

Instead, in this paper, we explore a novel approach that empowers interactive systems with direct control of the user's head orientation by actuating the user's neck muscles with electrical muscle stimulation (EMS). Our system is depicted in Figure 1 (a). The fact that it builds on EMS results in a haptic device capable of actuating the user's head without requiring any attachments on the user's face/head or above the neck muscles—e.g., a simple turtleneck would cover our system's EMS electrodes entirely.

As the first investigation of interactive head actuation, we first explored which muscles and electrode placements robustly actuate the user's head orientation. Then, in our first study, we characterized our system's accuracy while actuating participants' head orientations to static targets and trajectories. Then, we demonstrated how our electrical head actuation enables interactions not possible before by building a range of applications, such as directly changing the user's point-of-view to locate targets in a mixed-reality fire safety training and transmitting head nods from one user to another. Further, to gather more qualitative feedback about participants' experience with this novel type of haptics, we conducted a second study, in which participants explored our applications. We found that our head actuation positively shaped the participants' experience.

2 OUR APPROACH: ACTUATING HEAD VIA EMS TO NECK

2.1 Neck = uncharted territory for interactive EMS

While EMS to the neck muscles has been practiced in the medical field (mostly for rehabilitating swallowing disorders [4, 10, 29, 51] or neurological conditions such as hemispatial neglect [23, 49, 61]; pain therapy [39]; and even as an epilepsy treatment [9]), there are no prior works on interactive head actuation with EMS, hence there is little information about which neck muscles and electrode placement should a realtime, interactive system use to robustly actuate the head. In most interactive systems based on EMS [26, 34, 46, 48, 59], the approach to finding how to actuate a particular limb with EMS is: (1) consult the anatomical chart; (2) find at least two large muscles that pull and push the limb (i.e., a flexor and an extensor) (3) repeat this for each degree of freedom of this limb's joint; and, (4) *iterate* over each of these electrode placements to find suitable locations that actuate the limb while *minimizing cross-talk* between the different degrees of freedom and *minimizing unwanted movements* in adjacent muscles [47, 57, 59]. These two well-known limitations of EMS pose stark consequences for unexplored EMS regions. Often, the first researchers to interactively actuate an unexplored body part with EMS map the territory, i.e., explore which muscles and electrode placement can actuate robustly and ensure pain-free operation. As an example, the *PossessedHand* [59] was a pioneer interactive system in using EMS for individual finger movements; as such, much of their emphasis, even across multiple papers [58, 59], was characterizing electrode placement and its resulting accuracy. This is precisely the work that we present for the case of the neck muscles, which we hope will accelerate other researchers in exploring this new terrain for interactively controlling head movements.

2.2 Building the first map of neck muscles for interactive head actuation

The neck is a complex target for non-implanted EMS due to its 12 main muscles (and 6 additional minor muscles) [53], multiple attachment points (skull, hyoid bone, clavicles, and the sternum), and movement in three axis: cervical rotation (turning the head to the left/right), cervical flexion (nodding the head down to the chest) & cervical extension (nodding the head up to the back) and cervical lateral flexion (tilting the head to the shoulder) [22]. Figure 2 summarizes the 12 main muscles that are involved in each of these movements [53].

To gather intuition on which muscles are useful for neck EMS, we placed electrodes at all skin locations atop each of the nine superficial muscles (three muscles were found to be too deep for non-implanted EMS actuation) and observed the resulting neck movement during EMS actuation. These preliminary pilot tests allowed us to characterize which placements can robustly actuate the user's head without unwanted movements and enabled us to, later, build a neck-PID controller for each axis, which we describe in *Implementation.*

2.3 Tilting

As depicted in Figure 3, we found that tilting left/right (cervical lateral flexions) induced unwanted movements in the shoulders, i.e., involuntary shoulder shrug. To perform this movement with EMS, we explored all available muscles: *scalenes* and *levator scapulae*. Unfortunately, we concluded that their proximity to the shoulder muscles allows EMS currents to run through the shoulder and cause unwanted movements. Thus, we decided against using this direction of movement as it did not provide robust results.

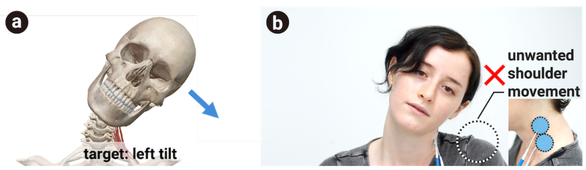

Figure 3: Electrode placement for head tilting induces large unwanted movements in the shoulders.

2.4 Turning left/right

As depicted in Figure 4, we found that turning left/right (cervical rotations) can be robustly achieved with EMS. We explored all available muscles: *splenius capitis, sternocleidomastoid, and splenius cervicis*. These muscles are bilateral, i.e., they run symmetrically in both sides of the neck, thus turning the head to one direction with any of these muscles is achieved by actuating only the corresponding side. More importantly, we observed that the *splenius capitis* was the only muscle to achieve this movement robustly (Figure 4b). The remainder muscles were found to be unsuitable: actuating *sternocleidomastoid* turns the head but induces unwanted tilting (Figure 4c); actuating *splenius cervicis* resulted in head nodding up (Figure 4d).

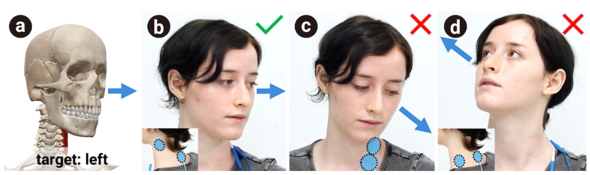

Figure 4: We found a placement that robustly turns the head left using EMS.

2.5 Nodding down

As depicted in Figure 5, we found that nodding down (cervical flexion) can be robustly achieved with EMS to *sternocleidomastoid*. As depicted in Figure 2, *sternocleidomastoid* was the only available muscle for this movement because the remainder muscles were unable to be stimulated via non-implanted EMS due to their depth (i.e., they are behind the larynx). More importantly, we also found that attaching one pair of electrodes (i.e., one EMS channel) per muscle, which is typical of interactive EMS systems [34, 38, 48] is not ideal for the *sternocleidomastoid* muscles. This is because two sternocleidomastoid muscles run symmetrically on both sides of the neck, thus, with one channel on each side, the resulting forces from both sides must be precisely equalized; otherwise, the neck will move down but *also tilt to the stronger side* (Figure 5c). We found this effect to be so strong that even a slight unbalance in electrode placement will cause unwanted movements. To mitigate this, as depicted in Figure 5 (b), we actuate the two symmetric sternocleidomastoid muscles via one EMS channel across both. We observed that this causes the EMS current to hit both sides of the muscles, in a more balanced fashion, resulting in a uniform downwards head nod; to the best of our knowledge, this electrode placement has never been explored before.

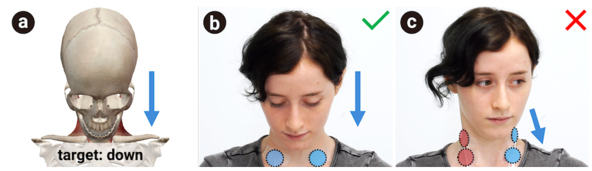

Figure 5: We found an electrode placement that robustly nods the head down with EMS.

2.6 Nodding up

As depicted in Figure 6, we found that nodding up (cervical extension) can be robustly achieved with EMS. We explored all available muscles: *splenius cervicis, splenius capitis,* and *upper trapezius*. Moreover, since all these muscles run symmetrically on both sides of the neck, we followed the same strategy used for nodding down: using one EMS channel for both sides. We found that both *splenius cervicis* (Figure 6b) and *splenius capitis* (Figure 6c) achieved upwards nodding robustly. In addition, we found that *splenius* cervicis outperformed *splenius capitis* with more range of upwards movement even at a lower EMS intensity. Conversely, we found that the *upper trapezius* did not result in upwards motions (Figure 6d).

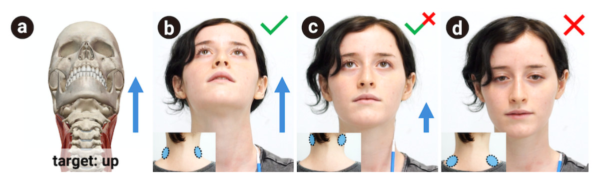

Figure 6: We found an electrode placement that robustly nods the head up with EMS.

2.7 Safety during EMS to the neck

To ensure operational safety during our head actuation via EMS to the neck, we follow the established safety guideline around EMS [28] by using a medically-compliant stimulator throughout the study [50]. The device has the following safety features: (1) electrode error detection (i.e., if the electrodes fall from a user, the device immediately halts all impulses); (2) current control (i.e., the output current amount is independent of skin resistance); (3) galvanic isolation (i.e., no physical connection between the user and other electrical sources). Moreover, we make sure the proper electrode placement before the stimulation so that electrodes are off from *carotid sinus*, which is, to our knowledge, the only nerve under the neck that can be stimulated by an EMS device and has a risk of causing side effects (prior research implied electrical stimulation to the nerve could decrease blood pressure [21]). Note that none of our electrode placements are atop the nerve in principle.

2.8 Summary

Our exploration provided the first map of which muscles can robustly actuate the neck in four directions (nodding up/down & turning left/right), which we use to demonstrate interactive uses of head actuation.

3 WALKTHROUGH: USING ELECTRICAL HEAD ACTUATION TO GUIDE ONE'S POINT-OF-VIEW

To illustrate the new possibilities enabled by our electrical head actuation, we demonstrate it in the example of a mixed reality (MR) application for fire safety training. Here, our user wears our electrical stimulation system on their neck as well as a HoloLens 2 MR headset, which displays the virtual content and tracks their head.

Figure 7: (a) The user sees a fire in the solder station; but, (b) cannot locate the fire extinguisher. (c) Our device changes the user's point of view by actuating their head orientation by means of EMS. Allowing the user to spot the extinguisher.

The user is at a laboratory, learning about fire safety from a first-person perspective, instead of with training videos. As depicted in Figure 7 (a), they see a fire breaking out at the solder station through the MR headset. Their goal is to put out the fire. The MR interface visually depicts the next instruction to the user, "Put out the fire". However, the user is having difficulties locating the fire extinguisher, which we depict in Figure 7 (b). Instead of the GUI elements that MR typically make use of to indicate off-screen

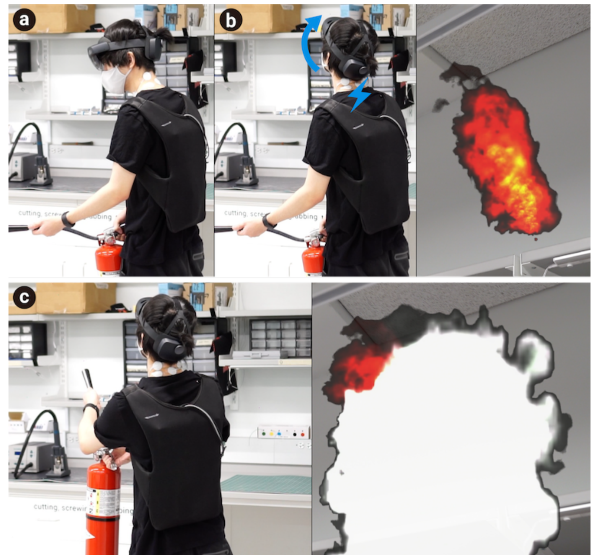

Figure 8: (a) While the user is putting out this fire, they forget to scan the surrounding for runaway small fires. (b) Our device uses EMS to change the user's point of view so that they see a fire on the upper shelf, which (c) the user tries to extinguish.

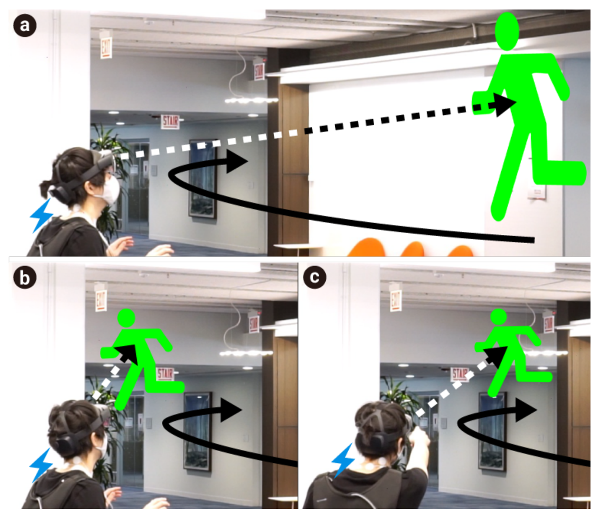

Figure 9: Our system actuates the user's head, in a *trajectory*, that follows the evacuation route. The exit symbol is also seen in MR by the user; here, for the sake of visual clarity, we added it in post-production.

targets, our system relies on a novel approach: it actuates the user's head to the *lower-left*, which is depicted in Figure 7 (c) so that the fire extinguisher comes into their view—in other words, our system actuates the head, which in turn guides the user's point-of-view (POV).

Now that the user has located the fire extinguisher with the help of electrical head actuation, they put out the fire. Our training

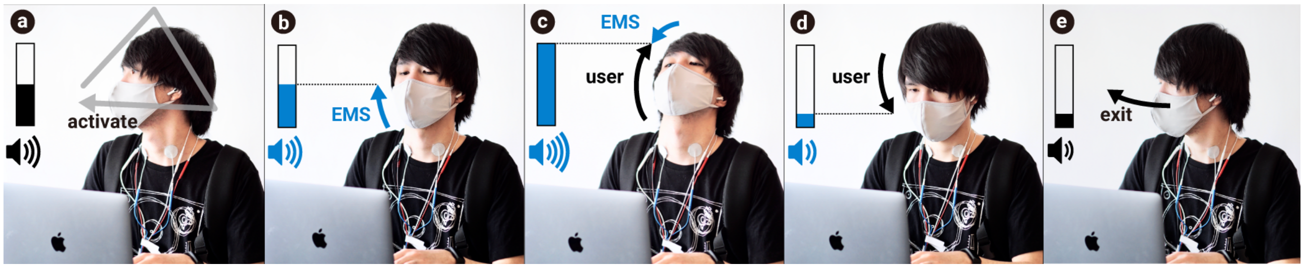

Figure 10: Our music volume controller depicts how a UI can use neck movements for both input and output.

simulator renders a virtual extinguishing smoke coming out of the fire extinguisher prop. While putting out a fire, safety guides indicate one must scan the surroundings for other runaway fires that might have spawned from the original fire. Unfortunately, the user does not see that the shelf above the soldering station is on fire. Figure 8 (b) depicts how our system assists in the training by actuating their head *upwards*, to the new fire.

Figure 8 (c) depicts the user trying to extinguish the fire. Unfortunately, the fire is breaking out in the ceiling, emitting toxic smoke. The rule in such a situation is: "once a fire starts to spread, your best option is to evacuate the building" [8]. As such, visual instruction urges the user to get out of the laboratory by means of the evacuation route. Amidst the smoke (virtually projected in MR), it is harder to find the route. Thus, as shown in Figure 9, our system assists the user by actuating their head in a *trajectory* to follow the exit symbol tracing out the evacuation route. This also demonstrates how our head actuation can be combined and complement visual cues by assisting the user to follow the moving visual target (i.e., exit symbol), that otherwise could be missed.

4 BENEFITS AND CONTRIBUTION

Our key contribution is that we propose a novel interface concept where interactive systems directly manipulate the user's head orientation and realize it by actuating the user's neck via electrical muscle stimulation. Our approach has the following three benefits. (1) A new channel for interactive systems to interface with the user's head, providing it different types of haptic feedback, such as guidance or force-feedback—this channel does not rely on any visual, auditory, or vibrotactile cues and can be used either as an alternative modality or in conjunction with existing approaches. (2) Our device does not require any facial attachments or bulky components, and it does not add any weight above the user's head. This enables applications outside of VR, in which users might not want to wear actuators on their faces. (3) Moreover, because our approach controls the user's head orientations in more directions (nod up/down, turn left/right, and all its diagonals) than prior work using head-mounted devices [14, 27, 32], we can build applications that were previously not possible.

5 DEMONSTRATING HOW DIRECT HEAD ACTUATION ENABLES NEW APPLICATIONS

Our electrical head actuation enables many types of applications, including some that were not previously possible. To demonstrate this, we implemented four classes of applications: (1) snapping to spatial information by guiding POV; (2) neck-based I/O interface; (3) transmitting neck movement to another user; and (4) force feedback around the head for immersive experiences. Although we exhibit each application in either mixed reality, virtual reality, or the real world, these applications can be implemented across all of them. Since our walkthrough covered (1) already, we describe the other three below.

5.1 Neck-based I/O Interface for Controlling Sound Volume

In this application, we depict how we built a type of application, in which a UI uses head movements not just as input but also as output, which demonstrates how our technique can be employed to close an I/O loop in the neck. Here, we demonstrate this with the example of a simple music volume controller that the user can adjust using head movements. As depicted in Figure 10 (a), the user activates the system by using a trigger gesture (a triangular head motion detected by the user's AirPods Pro earbuds with IMU tracking), while listening to music; (b) our system immediately takes over and renders the current value of the music volume by moving the user's head up with EMS; (c,d) now, by moving their head voluntarily up/down, the user adjusts the volume, and as they hit the ends of

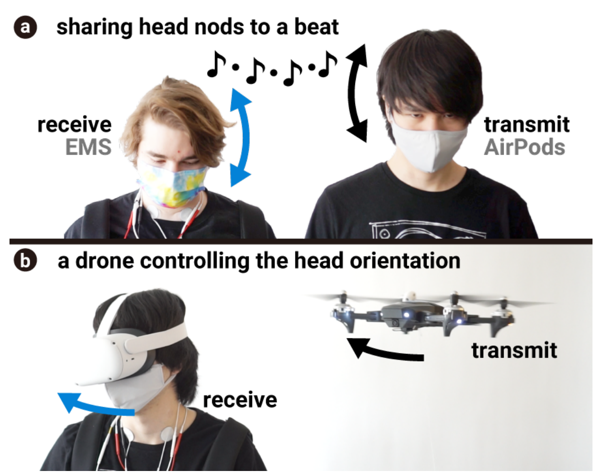

Figure 11: Our device can be used to transmit the head orientation between two users. (a) Two users nod to a beat in sync. (b) A drone's rotation dictates the user's neck movement.

the slider scale (i.e., maximum/minimum volume), the EMS pulls their head back in the corresponding direction to notify this; and, (e) when finished adjusting it, the user turns their head right to indicate the interaction is finished. Finally, while this example is a type of symmetric proprioceptive interaction (as in [34]), it is the first to extend this to the neck, which enables hands-free interaction.

5.2 Transmitting Neck Movement to Another User

We leverage our head actuation to transmit the movement of one user to another's neck. In Figure 11, we depict a simple application that allows a user to nod their head to a beat and transmit that rhythmic neck movement to a remote user wearing our system (Figure 11a). This is inspired by *bioSync* [46] but allows sharing neck movement rather than that of the arms. By attaching a tracker to a remote-controlled drone, it is even possible to transmit the drone's rotational movement to the user's neck (Figure 11b); this allows a new type of human-drone interaction by inverting the concept shown in *Flying Head* [18].

Figure 12: (a) The user is experiencing VR boxing. Our system renders force feedback of the (b, c) left/right hooks and (d) uppercut.

5.3 Rendering the Force Feedback of Punches in VR Boxing

While EMS has been explored in VR for creating force feedback, all existing systems mostly only provide forces to the user's arm, forearm, wrist, etc. Instead, in Figure 12, we demonstrate a boxing simulator in which the user feels the impact of left/right punches and uppercuts. This is inspired by *Impacto* [33] but depicts a novel use of EMS in that it allows the user to feel directional force feedback *on their head*.

6 RELATED WORK

Our work is built on interactive systems that physically actuate the human body, particularly those for the head and neck. Our work is also inspired by the more traditionally used modalities (e.g., visual, auditory, or tactile cues) to inform a user to voluntarily change their head orientation.

6.1 Traditional Modalities to Inform the User to Voluntarily Change Their Head Orientation

First, we review the more traditionally employed approaches that, instead of directly actuating the user's head orientation *involuntarily*, inform the user via visual/auditory/tactile cues that they should *voluntarily* change their head orientation. In HCI, these approaches are typical in interactive systems for navigation or view-finding.

Displaying visual icons (e.g., arrows, circles) that indicate spatial targets is a powerful method to guide a user's head orientation. For instance, *JackIn* utilizes these visual signs to allow a remote collaborator to communicate spatial targets from the local user's point of view [25]. *Visual Guidance* also utilizes these visual signs to guide a user's point of view in 360° videos [30]. *Outside-In* guides a user's POV in 360° videos by visualizing the regions of interest that are outside of their field of view with picture-in-picture previews [31]. Peripheral LED displays attached to head-mounted-displays (HMDs) can also be utilized for guiding the user's POV [12, 13, 63]. Similarly, *Spider Vision* blends the views from two cameras attached to the front and the back of the user's head on the user's HMD so that they can see the rear view without looking back [7].

Auditory stimuli have also been leveraged for guiding head orientation. For instance, Yang et al. demonstrated that spatialized auditory beacons are useful to find target objects in MR remote collaboration [65]. Taking this further, *HindSight* automatically detects both static and moving target objects in the user's 360° surroundings and notifies the user of their locations by assigning spatialized sound cues to the target objects [54].

Furthermore, vibrations can also be used to guide head orientation; typically, researchers engineer neck-worn or head-worn vibrotactile devices. For instance, *HapticPointer* uses 16 neck-worn vibrotactile actuators to notify the user of 3D targets' directions [43]. *Haptic Collar* uses eight neck-worn actuators to assist users in navigating to a target destination [52]. *Neck Strap* renders two-dimensional spatial directions by modulating waves of vibrations from one neck-worn actuator [64]. Moreover, larger haptic devices capable of strong forces can even rotate the user's whole body to face a new direction. For instance, *SwiVRchair* directly rotates the user's body with a motorized swivel chair [15]. These motion platforms provide new automatic ways to guide head orientation, but they, unfortunately, are bulky and only suited for experiences where the user is sitting or standing *inside* the grounded device; moreover, these devices actuate the user's full body and not the just their head; Thus, as we will see next, researchers have been exploring ways to *mechanically* and *automatically* move the user's head orientation.

6.2 Mechanical Devices that Actuate the User's Head

Albeit robotic exoskeletons are the mainstream way to directly actuate one's body, robotic head actuation is still an emerging topic; so far, only used in medical rehabilitation. Only recently, a few robotic exoskeletons have been engineered for actuating a patients' neck [62, 67, 68]. In particular, Zhang et al. proposed the *Robotic Neck Brace*, the first and only wearable exoskeleton that manipulates the user's head around three rotational axes (i.e., roll, pitch, yaw) using large mechanical linkages attached to the user's forehead and shoulders that are controlled by servo motors [67]. These researchers have characterized the neck motion of patients with amyotrophic lateral sclerosis (also known as ASL) using this neck-worn exoskeleton [69]. So far, no robotic neck actuators have been utilized for building interactive systems.

In the field of virtual reality haptics, researchers have developed devices that provide force feedback around the user's head. For instance, *GyroVR* is a flywheel device attached to the user's VR headset that can render inertia around the head during head rotations, leveraging the gyroscopic effect [14]. *HangerOVER* is a force illusion that generates a yaw-axis pseudo-force by applying multiple points of normal force around the head, which causes the user to rotate their head involuntarily; this effect is known as the hanger reflex [27]. Finally, *HeadBlaster* utilizes air propulsion forces around the head to create left/right and front/back accelerations by emitting compressed air from nozzles attached to the HMD [32]. While these devices have their unique affordances, they also come with severe limitations: (1) the gyroscopic effect cannot render force when the user's head is static [14]; (2) as with most illusions, the hanger reflex is notoriously difficult to control for precise rotation angles [27]; and (3) devices based on air propulsion force requires large air compressors (200L), which limits the user's mobility [32].

We take inspiration from all these works but, instead, are the first to explore how electrical muscle stimulation (EMS) allows interactive systems to directly actuate the user's head.

6.3 Interactive Systems that Actuate the User's Body via Electrical Stimulation

In contrast to mechanical-based haptic devices [2, 6, 11, 45, 70] that, inevitably, are constructed from heavy and bulky actuators, researchers started engineering interactive systems based on electrical muscle stimulation (EMS). Unlike exoskeletons, EMS allows for unencumbered actuation, which is increasingly popular for mobile haptics systems, in which the user roams freely in their environment (e.g., as in untethered VR or AR experiences).

Over the last decade in HCI, researchers built a plethora of these interactive systems based on EMS, with the largest emphasis being on actuating the arms, wrists, and fingers with EMS. For instance, *PossessedHand* is an EMS-based system that assists users in learning a new musical instrument by actuating their fingers [59]. *Pose-IO* is an EMS-based eyes-free I/O interface that reads and writes the position of the wrist [34]. *Affordance++* is an EMS-based system that assists users in interacting with objects they have never seen before [35]. Researchers have even actuated the user's hand or index finger to follow 3D targets [26, 44], which we take inspiration from but expand to the neck. Finally, a number of EMS-based systems have been engineered as a means to provide force feedback in VR [33, 36] or AR [37].

While most of the aforementioned EMS systems focused on actuating the user's upper limbs, EMS has also been used to interactively manipulate lower limbs. For instance, *Footstriker* assists the user to keep a proper running form by correcting their mid-air leg posture while running [17]. Moreover, *CruiseControl* is an EMS-based interactive system that actuates the user's leg rotation to achieve redirected walking [48]. Finally, prior work also actuated the sense of balance using galvanic vestibular stimulation (known as GVS) [40, 56]. This type of electrical stimulation induces a sense of imbalance, which in turn, causes a reflex where the user shifts their center of balance with their whole body, subsequently, this also causes movement of the user's head.

The critical difference between our work and these prior works is that our system directly actuates the user's head by actuating the neck muscles, which—to the best of our knowledge—have never been explored for EMS-based interactive systems. Moreover, it is by actuating the neck that our system also gains access to manipulating the user's point-of-view (POV), enabling expressive applications other than just force feedback.

7 IMPLEMENTATION

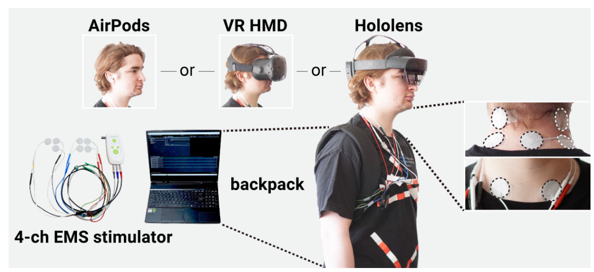

Figure 13: Our wearable system setup.

To help readers replicate our design, we now provide the necessary technical details. Additionally, all source code and materials are made publicly available[1].

7.1 Hardware

Figure 13 depicts our wearable hardware setup that ensures a user's mobility. The system stimulates the user's neck muscles at 30 Hz using a medical-grade electrical muscle stimulator (HASOMED *RehaMove3* [50]) which the user carries in a slim backpack. Our system utilizes four channels of the EMS stimulator to actuate the head accordingly to the electrode placement found in our preliminary exploration: (1) turn left by stimulating the left side of the *splenius capitis*; (2) turn right by stimulating the right side of the *splenius capitis;* (3) nod up by stimulating the *splenius cervicis;* and (4) nod down by stimulating the *sternocleidomastoid.*

For tracking head orientation, we made our system compatible with HoloLens 2 [20], HTC VIVE, and AirPods Pro earbuds, such that the user equips one of them based on the application type (i.e., MR, VR, and real environment). The interface between the EMS stimulator and the tracking device(s) is a laptop (MSI GL65 Leopard) running our Unity3D applications; the laptop is also stored in the user's backpack.

7.2 EMS Control Loop

PID-based control for static targets. To actuate the user's head to a target orientation, we implemented a PID controller, designed specifically for neck EMS. The PID controller regulates the pulse-width of the EMS impulses between the range of 0 μs and 300 μs.

[1]https://lab.plopes.org/#electrical-head-actuation

In each cycle, the system calculates the error $(e_x,\ e_y)$ between the user's head orientation, given by the current orientation (obtained from tracking), and the target orientation. Note that the x axis here represents head rotations around the yaw axis (i.e., turn left/right) and the y axis represents head rotations around the pitch axis (i.e., nod up/down). With the input of e_x and e_y, our PID controller individually computes PW_x and PW_y, which are final EMS pulse-widths for actuating the user's neck to turn horizontally and/or nod vertically towards the target respectively. Our controller is dual in that, if PW_x is positive, it will be set as the pulse-width for the right-channel; if PW_x is negative, it will be negated and set as the pulse-width for the left-channel; similarly, if PW_y is positive, it will be set as the pulse-width for the up-channel, and vice-versa for the down-channel. For instance, in one cycle, $(PW_x,\ PW_y) = (-100,\ 200)$ dictates that left-channel outputs a 100 μs pulse and up-channel outputs a 200 μs pulse (i.e., no pulses are output from right-channel and down-channel). Via initial pilots, we settled on the following PID coefficients $(Kp,\ Ki,\ Kd)$: $(16,\ 4,\ 2)$ for static target acquisition. Finally, note that our PID controller works without any voluntary movement by users; if the neck's own springiness or the user moves away from the target, the PID will push it back without user intervention.

PID tuning for pursuing trajectories. To actuate the user's head to pursue a trajectory, our system moves the target orientation along the trajectory on a real-time basis. Unlike the static targets, we adopted the PID coefficients of $(Kp,\ Ki,\ Kd)$: $(64,\ 4,\ 2)$, since we found that they provide faster acquisition, which is important for trajectories, without much noticeable error increase. We also found that, even with the increased Kp, the head actuation often falls behind the target's movement and the errors accumulate over the pursuit. To address this issue, the software-side of our system control the target's speed in real-time so that the angular distance between the user's head orientation and the target orientation is always smaller than a certain threshold, i.e., when the error surpasses the threshold, the target stops and waits for the user's head orientation to catch up, and once the error becomes smaller than the threshold, it starts moving again.

PID discussion. From these empirically determined coefficients, we can intuit that the main factor driving the pulse-width is the Kp coefficient (the linear adjustment based on an error to target) with minimal contributions from the Ki and Kd coefficients. However, we also noted in our pilots that the neck muscles tend to dampen movement more than the extremities (e.g., arms), which might explain the relatively low values of I and D coefficients while preventing the resulting actuation from overshooting or oscillations.

7.3 Extending Our System in Unity3D for Developers

We provide two types of Unity3D prefabs that encapsulate the functionality of our system, making it easy to add to existing applications developed in Unity 3D (not limited to VR). Figure 14 shows a screenshot of a user using our prefabs to add electrical head actuation to their VR safari. UI developers drag and drop the prefab of their choice to a 3D object that they wish the user to acquire using EMS-based head actuation; our system will automatically handle the target orientation calculation, initiate communication with the EMS device, and start the PID controllers. As depicted in Figure 14, these simple Unity3D prefabs allow developers to assign both *static targets* (e.g., the elephant) as well as *trajectories* (e.g., the flying bird). After assigning the latter, the prefab allows a developer to define the shape of the trajectory by directly drawing it using *Bézier Path Creator* [3]. Then, they can fine-tune the speed of the moving target.

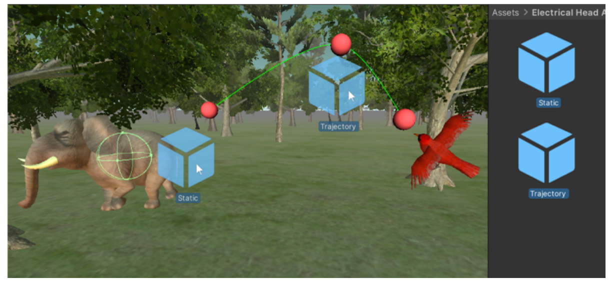

Figure 14: Our Unity3D prefabs in action while developing a VR safari.

7.4 Tracking, Display, Communication and Latency

Our head actuation system was implemented to be agnostic of the tracking system as long as it provides rotational tracking of the user's head. We implemented bridges between our system and the three external tracking systems, which afford different use cases. Note that in all our applications, users tend to wear the complete system on their body, typically in a backpack. Naturally, the choice of a tracking system impacts the quality of the resulting applications, i.e., using room-level positional tracking (e.g., HTC VIVE or Hololens 2, which we use for our VR and MR applications) allows applications to actuate the user's head to point to targets in physical space; conversely, using only inertial-based tracking systems (not positional) allows applications that actuate the user's head with respect to the inertial frame of reference (e.g., IMUs from AirPods Pro, which we use for our *neck-based I/O* or *transmitting neck movement* applications).

MR tracking. We leverage the tracking of the *Hololens 2* to track both the user's head position in space and its rotation. This data is streamed in real-time from the headset to the laptop running the Unity application via Wi-Fi, built on top of the *Holographic Remoting Player* API [19]. Using the same communication channel, the laptop streams and displays visual MR scenes to the user's headset.

VR tracking. We leverage the tracking from the *HTC Vive* system, using its base stations and the headset.

Mobile tracking. In our most mobile and minimal tracking implementation, we leverage *AirPods Pro*, which tracks only the user's rotation with its inertial measurement unit. The sensor data is retrieved via Apple *Core Motion API* [5]. Since the API can only be accessed from iOS, the sensor data is first streamed from an iOS device (*iPhone 11*) and relayed to the laptop via Open Sound Control over Wi-Fi.

End-to-end latency. In our most extreme applications that run over the Wi-Fi (e.g., transmitting head nods to a remote user) our system has an end-to-end latency of around 246 ms (calculated from high-speed video).

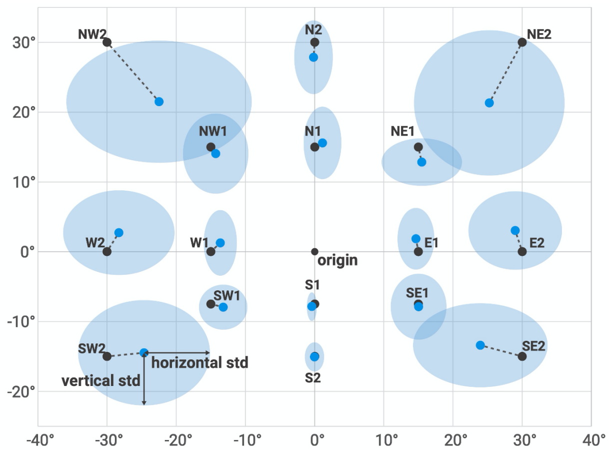

Figure 15: The results for acquiring static targets in eight directions with two distances. The dashed lines represent the distance between the targets (black points) and the overall mean output head orientations across all participants (blue points). The blue ellipses represent the standard deviations of the mean outputs.

8 USER STUDY #1: EVALUATING THE ACCURACY OF OUR HEAD ACTUATION

To understand the quality of our system, we conducted a user study comprised of two tasks, each focused on evaluating a different function of our technique: (1) acquire static targets and (2) follow trajectories.

Participants. We recruited seven participants (five identified as male, two as female, average age = 25.6 years, SD=1.4) from our local institution. Six participants had previously experienced EMS on their arms, but none had experienced it in the neck. We excluded one participant from the analysis who, unfortunately, did not have enough time for the completion of all trials as each study session took about 1.5 hours to complete.

Apparatus. Participants wore our EMS electrodes, stimulator, and a Hololens 2. We used the headset *only for tracking* and nothing was displayed during the study. According to a prior work that evaluated the accuracy of this tracking device on participants' heads [16], we established that its accuracy was sufficient for our study.

Calibration procedure. Prior to the actual trials, we first calibrated the amplitude of EMS currents for each participant. For calibration, we applied a constant EMS pulse-width of 300 μs. Starting from 0 mA, we increased the current by 1 mA steps, while ensuring pain-free operation prior to the next increase. We repeated these 1mA increase steps until the participant's head rotates at least up to 30° for left/right/up movements and 15° for down movement. This ensured that the EMS was able to robustly actuate all the participant's heads by this quantifiable threshold. We repeated the above calibration procedure for all four EMS channels (i.e., left, right, up, and down).

8.1 Task #1: Acquiring Static Targets in Eight Directions

In this first technical evaluation, we measured how our system actuates and holds the participants' head orientation at 16 static target positions: eight "cardinal" directions (N, NW, W, SW, S, SE, E, NE) × two distances (the darker points in Figure 15). We denote targets by their cardinal direction and the numeral 1 or 2 for their distance (i.e., NE2 stands for the furthest target in the Northeast direction). Target placement was inspired by the anatomical range of the neck and the actuation range observed in our pilots. Importantly, to evaluate the system's actuation ability, we asked participants not to voluntarily move their neck during the trials.

Procedure. We asked participants to relax their neck in its neutral position, which we define as the origin for a trial (the center black dot in Figure 15). Then, after a randomized waiting period, the EMS was applied for six seconds, regulated by our PID controller, so that the head *reaches and stays on* the target. We compute the final head orientation by averaging the head angles in the final second of the trial and calculated its error (i.e., distance) to the target. Each participant performed 32 trials in a randomized order (16 targets × 2 repetitions).

Results. Figure 15 depicts the overall mean outputs (blue points) and their standard deviations (blue ellipses) for acquiring all 16 targets across all trials (6 participants × 2 repetitions).

We observed a mean error of 7.55° (SD=5.89°) across all targets and trials. Secondly, we observed a smaller error for the closer targets than for the further away distances. Moreover, we observed a compounding effect of PID errors when actuating in two directions simultaneously; in other words, the diagonal directions tend to exhibit more error to target than N, S, W, E. To provide readers with a detailed understanding of the error for each target, we also report the mean error and its standard deviation (SD) for each target in Figure 16. Finally, we found that on average, for all 16 targets, it took 2.60 s (SD=0.79) for our system to acquire a static target. To calculate this, per trial, we measured the elapsed time from the start of a trial until the participant's head reached the final head orientation (i.e., the average of the participant's head rotation in the last second of a trial; as such, this measure discounts stabilization or oscillation time).

8.2 Task #2: Pursuing Trajectories

In the second task of our technical evaluation, we measured how our system actuates the participants' head orientation to follow three simple types of trajectories: a horizontal back-and-forth trajectory,

Target	W1	W2	E1	E2	N1	N2	S1	S2	NW1	NW2	NE1	NE2	SW1	SW2	SE1	SE2
Mean (degree)	4.87	9.13	4.7	8.08	4.94	5.69	1.65	2.18	6.41	18.07	5.94	16.27	4.63	12.25	5	10.94
SD (degree)	2.37	4.58	2.47	4.1	3.07	2.32	1.43	1.04	3.42	6.14	3.43	6.58	1.66	3.77	3.35	6.46

Figure 16: Mean errors and their standard deviations (SD) for all 16 targets.

a vertical back-and-forth trajectory, and a sinusoidal trajectory, which are shown in Figure 17. Again, to focus on evaluating the system's actuation ability, we asked participants not to voluntarily move their neck during the trials.

Procedure. We follow the same procedure as the previous task. When we start EMS stimulation, our PID controller actuates the participants' head orientation to follow the moving target along a trajectory. We stop the stimulation at 0.2 seconds after the target reaches the end of the trajectory to account for the delay between the head's movement and the target. Note that stimulation periods may vary across trials since the speed of the target changed according to the error. We implemented these moving targets as follows: the target moved at 60 degree/sec, and when the error surpassed 15°, the target stopped until the error was below 15°. We track the participants' head orientation and calculate the error to the target point on the trajectory at every time step during the stimulation. Participants performed six trials in a randomized order (3 trajectories × 2 repetitions).

Results. Figure 17 depicts average trajectories (thick blue lines) and raw trajectories (light blue lines) derived from all participants' data for the three target trajectories. To obtain the average trajectories, we equalized the data length of each trial by means of time normalization.

For the horizontal back-and-forth trajectory, depicted in Figure 17 (a), we observed a mean error of 8.92° (SD=4.56°) across all time steps and all trials. As shown in the box plots in Figure 17 (a), we also quantified horizontal under/overshoot of the PID around the trajectory's leftmost and rightmost points based on the leftmost and rightmost points that the participants reached. We found that a mean output horizontal angle for the leftmost point was -25.21° (SD=4.98°) and that for the rightmost point was 25.3° (SD=6.87°) across all trials.

For the vertical back-and-forth trajectory, depicted in Figure 17 (b), we observed a mean error of 8.0° (SD=3.32°) across all time steps and trials. Again, we also quantified vertical under/overshoot of the PID around the trajectory's top-most and bottom-most points depicted in the box plots in Figure 17 (b) based on the top-most and bottom-most points that the participants reached by calculating the standard deviation of the trajectory's top-most and bottom-most points, which depict sharp (180°) turns in motion. We found that a mean output vertical angle for the left-most point was 25.8° (SD=2.79°) and that for the right-most point was -16.1° (SD=4.57°) across all trials. In line with our previous study, this suggests that the vertical axis (up/down) has the best precision, compared to the horizontal axis (left/right).

For the sinusoidal trajectory, depicted in Figure 17 (c), we observed a mean error of 11.41° (SD=3.76°).

Finally, the technical evaluation also demonstrated that our system is relatively fast for EMS-based dynamic target acquisition. Our system actuated participants' heads to acquire these trajectories in < 10s (for comparison, *Muscle-plotter* takes 16.2 s (SD=4.9 s) to plot trajectories by actuating the wrist [38]), specifically taking an average of: 7.83 s (SD=3.5 s) for the horizontal trajectory; 5.58 s (SD=4.69 s) for the vertical trajectory; and, 6.03 s (SD=5.33 s) for the sinusoidal trajectory.

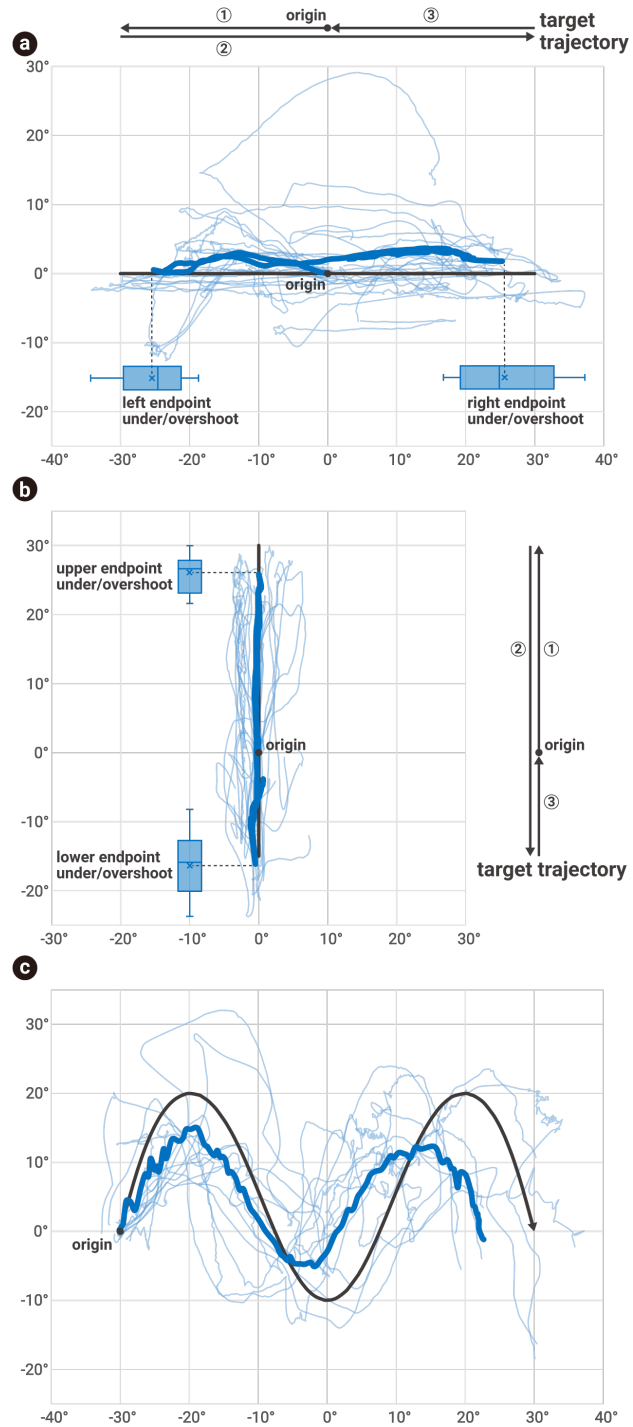

Figure 17: The results of the trajectory acquisition (a) horizontal back-and-forth; (b) vertical back-and-forth; and, (c) sinusoidal. (black lines depict target trajectories, blue curves depict average trajectories and light-blue curves are raw trajectories).

8.3 Framing Our Results in the Context of Our Proposed Applications

We now discuss the resulting accuracy found in our study (ranging from an average of 7.55° for static target acquisition up to an average of 11.41° for acquiring targets on a sinusoidal trajectory) with our four applications presented in Section 5. First, for applications in which the neck-based interactions are the only available modality, such as our *Neck-based I/O* or our *Transmitting Neck Movement* applications, the resulting accuracy directly limits the applications' resolution. In this case, we recommend that these applications are designed with the accuracy limitation in mind. For instance, a designer can space static haptic events within the user's range of head orientation at least 7.55° apart. On the other hand, for applications in which the head actuation provides an additional modality, the resulting accuracy might not dramatically impact the applications' resolution. For instance, the resulting accuracy is well suited for force-feedback-based applications, such as our *VR Boxing* application, since these require a coarser type of head actuation. Moreover, for POV guidance applications, such as our *AR Fire Safety* application, one can frame the above results while taking the size of a user's field-of-view (FOV) into consideration. Specifically, one can consider the focused area of the FOV, which roughly comprises a square of ±15° (horizontal angle) × ±15° (vertical angle), where users reliably recognize symbols [42]. While the overall mean error such as 7.55° (for static targets) and 11.41° (for the sinusoidal trajectory) might appear as a large error when thinking of gaze (eye movements), it is relatively small for one's point-of-view since it is still within the focused area of FOV. In other words, missing a target by 7.55° implies this target can be still seen as a symbol in one's POV [42]. However, those of NW2 (Mean: 18.07°, SD: 6.14°) and NE2 (Mean: 16.27°, SD: 6.58°) are proximal to this boundary, implying that a user might miss those targets.

9 USER STUDY #2: EXPLORING THE EXPERIENTIAL SIDE OF ELECTRICAL HEAD ACTUATION

While in our first study, we validated the accuracy of actuating participants' heads to different angles, we now turn into understanding users' experiences while wearing our system. This study was not designed with the intention of evaluating performance-specific metrics, or comparison to other modalities, but instead, of extracting insights from participants' comments or behaviors while using our system. This study was approved by our Institutional Review Board (IRB21-1158).

9.1 Study Design

Participants. We recruited eight participants (five identified as male, three as female, mean age = 22.1 years old; SD=2.1) from our local institution; none had partaken in our first user study and never experienced EMS on their neck. Each study took about 1.5 hours to complete. Participants received 50 USD as compensation.

Tasks. Participants explored our four applications adapted to fit the study format: (1) *AR fire safety,* we asked participants to find a real hidden fire extinguisher and put out four virtual fires hidden around the room. Our system guided their head to the next target when they were less than 2.5 meters away from it. Also, to facilitate participants' input while holding a heavy fire extinguisher as a prop, we asked participants to verbally say "press" and the experimenter sent a message to the HoloLens application via Wi-Fi that triggered a virtual extinguishing smoke and put out the fire. (2) *Sound control,* we asked seated participants to use our system to adjust the sound volume of a background music track to specific volume settings, while also watching YouTube on a tablet device; for simplicity, we omitted the activation gesture and instead the system activated itself at four pre-determined moments. (3) *Nod to the tempo,* this task was a variation of our previous *transmitting neck movement* application, but we asked participants to drum along to the tempo that they felt via the EMS-induced head nods. To make this experience comparable across participants, instead of transferring the head nods from the experimenter to the participant, we utilized a pre-scripted tempo, which participants had no prior knowledge of. This tempo started at 45 bpm and shifted every 30 seconds: first to 55 bpm, then down 30 bpm, and finally, up to 45 bpm. (4) *VR boxing*, we asked participants to play a boxing match against a virtual avatar controlled by the experimenter. To make the experience's duration consistent across participants, the avatar fell on the mat once participants punched it after two minutes have elapsed.

Procedure. We calibrated our EMS device to robustly actuate the participant's head in all directions, while remaining in pain-free operation, following the same procedure as in our first study. Then, they experienced all four applications in a counterbalanced order. We made sure that they interacted with each application for at least two minutes. Moreover, since the objective of this study was to extract insights from the participants' experience, we asked participants to "think out loud" and voice any comments also during the trials. With their consent, we videotaped and transcribed the study.

Interviews. We followed each trial with a semi-structured interview, which started with two general experience-related questions using a 7-point Likert scale: (1) "How much did the head actuation contribute to your experience?" and "How much did you enjoy the experience?"; for each question, we followed by asking "why?". Then, we followed with a set of questions that allowed us to elicit comments about the participants' direct experience: (3) "In your own words, can you tell us what you thought the head actuation was trying to depict in this application?"; (4) "How it felt when the EMS first moved your head in this application"; (5) "How did you feel about the remainder head actuations in this application". After participants finished all four trials, we invited them for a final interview, which was guided by the following questions: (6) "What else could you imagine yourself using this technology being for?"; (7) "What aspects of this technology do you think need to be improved?"; (8) "Any other aspect of your experience that you would like to share with us". Finally, we conducted a post-study survey to collect feedback (in the form of open-ended questions) regarding the participants' comfort and perceived safety while using our system.

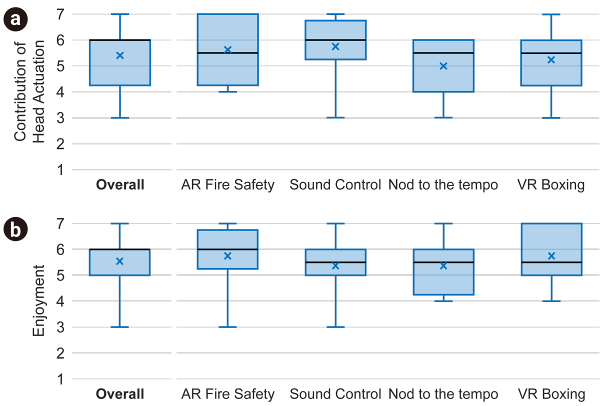

Figure 18: Participants raring to the contribution of head actuation to their experience and enjoyment (black line: median).

9.2 Results

Figure 18 depicts participants' overall ratings aggregated across all applications regarding the contribution of head actuation to their experience (M=5.4; SD=1.2) and their enjoyment (M=5.6; SD=1.1), suggesting that participants overall felt that the head actuation contributed positively to their experience and resulted in an enjoyable experience. As for the contribution of head actuation to their experience, per application, we observed: *AR fire safety* (M=5.6; SD=1.3), *sound control* (M=5.8; SD=1.3), *Nod to the tempo* (M=5.0; SD=1.2), and *VR boxing* (M=5.3; SD=1.3). As for participant's enjoyment, per application: *AR fire safety* (M=5.8; SD=1.3), *sound control* (M=5.4; SD=1.2), *Nod to the tempo* (M=5.4; SD=1.1), and *VR boxing* (M=5.8; SD=1.2). Now, we turn our attention to the participants' comments and observed behavior.

AR fire safety (Figure 19 a,b)**.** All participants described how the head actuation helped them by guiding their point of view; the comments included "the [actuation] helped me pinpoint where exactly I need to look at" (P2) or "it definitely helped by directing me (...) so if I didn't have that I would never be able to find the fire" (P3). P6 described their impression on the head actuation: "initially, I was expecting [the actuation] to feel unnatural, (...) but when I saw the extinguisher, it felt natural". P7 reasoned that the system's helpfulness was akin to a remote collaborator: "felt like somebody in a command center who has a better view of the environment (...) was guiding me".

Sound control (Figure 19 c,d)**.** Six participants described the head actuation as useful in adjusting the volume; the comments included "in terms of multitasking (...) it was very effective" (P1). Three participants mentioned the usefulness of the system depicting the endpoints of the volume scale, such as P6: comments included "it's very useful because it tells me when the volume goes over the maximum or below the minimum by pulling my head back". By utilizing this haptic information, P7 playfully maximized and muted the sound according to the beat of one of the songs (see our video figure). P5 and P7 justified their enjoyment from their bidirectional relationship with the system; for instance, P5 stated "I really enjoyed me being in control with the system (...) but also me controlling the system with my head".

Nod to the tempo (Figure 19 e,f)**.** Five participants described how the head actuation helped them feel the tempo. Their comments included "it was pretty effective (...) I was able to clearly feel which bpm [beats per minute] I was supposed to play" (P4), or "after a couple [of actuations], I felt I was able to anticipate the tempo" (P2). P2 also stated how they felt during the head actuation: "the head bobbing made me feel more physically in sync with the rhythm". Surprisingly, P8 regarded the head actuation as not only depicting the beat but also another person's musical intentions: "[the actuation] let me know what the other individual is thinking (...) and the music rhythm". We observed that, after a while, some participants enjoyed amplifying the EMS-induced head nods by voluntarily nodding stronger at the same time, while others let the EMS do all the nodding.

VR boxing (Figure 19 g,h)**.** Six participants described how the head actuation added realism; their comments included "without

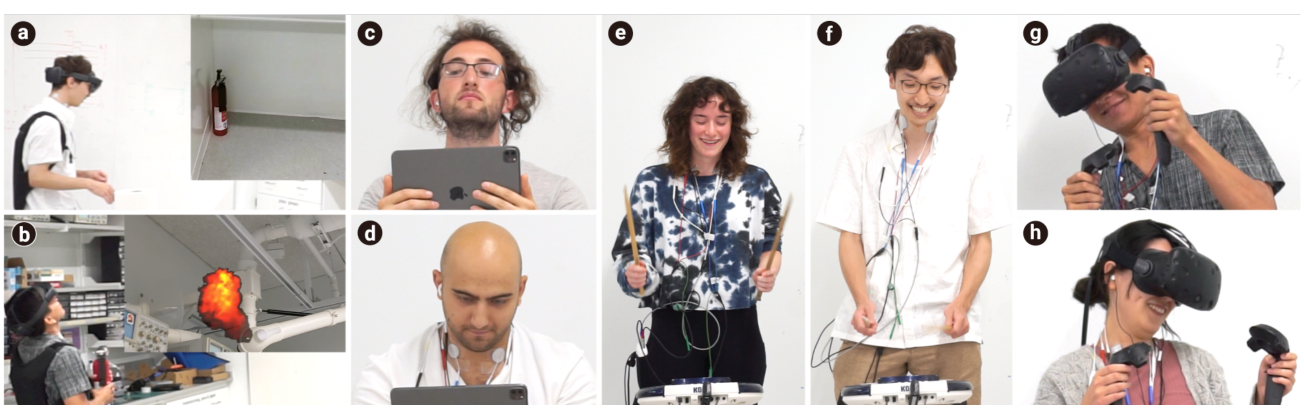

Figure 19: Photos from participants using our system (reproduced with participants' consent). The system actuates the participants' heads to look at the fire extinguisher, or the fire above (a,b). The system moves the head upward and downward to communicate the sound volume of background music (c,d). The participants enjoy playing the drum while feeling the tempo via up-down head actuation (e,f). The participants feel the haptics of left and right punches in VR (g,h).

it, (...) it would be so much more boring [because of] no genuine physicality to the person" (P1), or "the punches feel material and [it] definitely feels more like boxing environment" (P8). We observed that P2 was so immersed that they stepped back and kept a distance from the boxer in VR as if it was a real fight (see our video figure), which they also alluded to during their interview: "I did feel really immersed at one point when there was a kinda standoff where I wasn't punching and he wasn't (...) it felt like the stakes were higher".

How did you feel regarding the actuation? First, regarding the sensations evoked by EMS actuation, all participants mentioned that they became increasingly "used to" the head actuation as the experiences progressed. We saw this at the single application level, as highlighted by comments such as "after a few times, it became a lot more fluid" (P1, during *AR fire safety*), and "it was surprising at first and I felt a little bit rigid but, after a while, I got more used to it" (P2, during *nod to the beat*). Moreover, we also saw this effect across the duration of the study, as highlighted by comments such as "at this point, [since this was their fourth trial] (...) I'm pretty used to it" (P4, during *AR fire safety*) and "it was quite expected, (...) I already knew how the system works, so I didn't get surprised" (P5, during *sound control*). With regards to perceived safety and comfort, which we probed via our post-study survey, all participants described they "felt safe" during the study; the comments included "due to its adjustability it was a safe and easy process" (P3), or "I thought the incremental increase of the charge level [during the calibration] (...) gave me a sense of safety" (P7). As for their comfort, four participants mentioned directly that "it was comfortable"; conversely, the remaining participants had some mention of discomfort mostly associated with the tingling sensation caused by EMS; the comments included "the electric pulse produces discomfort during usage [while it] doesn't cause pain" (P8). Moreover, P8 also added that "the involuntary muscle contractions feel quite disturbing", a type of reaction that is not uncommon to EMS, likely attributed to losing the sense of agency [24].

Application ideas. Five participants described applications related to guiding one's point of view, such as "narrating VR theater contents by directing user's attention" (P2) and "street navigation using [head actuation]" (P4). P6 and P7 proposed the use of our system for potentially improving the user's incorrect neck posture.

Improvement suggestions. Six participants felt the EMS calibration needs improvement. Five suggested to make it faster, such as P4: "would need to be quicker (. . .) it would deter people from casually using it" or P7 who suggested eliminating manual calibration for an automatic calibration: "you can use sensors to auto-calibrate these things [EMS]". Moreover, P1 and P7 suggested that the device could be further miniaturized to "something like a necklace or a neck brace" (P1) and " make these things (. . .) invisible" (P7).

10 LIMITATIONS

First, like any other interactive systems based on EMS, our system requires calibration and has limited accuracy/range, which we found in our study to be overall 7.6° error for pointing static targets and 9.4° error for following trajectories within the following range: 30° in the left/right directions; 30° in the up direction; and 15° in the down direction. Second, our system can only move the user's head orientation to anatomically reachable targets (e.g., it cannot rotate the user's head by extreme angles, such as 180°), instead camera+HMD combinations can show a view of what lies behind the user [1, 7, 31]. Third, while actuating the user's head orientation might prove useful for interactive systems to guide the user's point of view, we acknowledge this is not the only factor that determines where a user is looking since the user's gaze are a key factor to navigate inside their field of view determined by their head orientation. Lastly, as a consequence of our exploration of which muscle sites are robust for actuation of the head around independent degrees of freedom, we found that tilting the head to the left/right shoulders was not independently actuated without inducing parasitical motion on other directions; thus, unlocking these might require future research.

Finally, it is important to note that we do not think of our novel neck-EMS technique as a means to replace existing (visual, auditory, tactile) cues to guide head movements but rather as a new and complementary modality that will also enable novel applications and can be combined with prior work.

11 CONCLUSIONS AND FUTURE WORK

We proposed, engineered, and explored a novel interface concept in which the interactive system actuates the user's head orientation. We implemented this concept by applying electrical muscle stimulation (EMS) to the user's neck muscles, enabling our system to actuate the user's head orientation around its yaw and pitch axis.

As the first exploration of EMS for head actuation, we characterized which muscles can be robustly actuated. Second, we evaluated the accuracy of our system for actuating participants' head orientation. Third, we demonstrated how it enables new interactions by building a range of applications. Finally, in our second study, participants felt that our head actuation contributed positively to their experience in four distinct applications.

We believe our work will inspire researchers to further delve into this avenue of *directly* controlling the user's head orientation. We believe there are several ways that researchers can further expand on our work, and, to accelerate this, we have provided all the source code[1]. Possible future investigations include exploring how electrical head actuation (1) interacts with eye-tracking and visual gaze redirection, (2) impacts the sense of agency (i.e., "who is looking at the target" [24]), (3) might enable to control the user's neck posture over time (e.g., which has been explored also via a robotically actuated computer monitor [55]). Our work provides a foundation for researchers to explore these challenges and expand on our findings or system in novel directions.

ACKNOWLEDGMENTS

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