RESEARCH-ARTICLE

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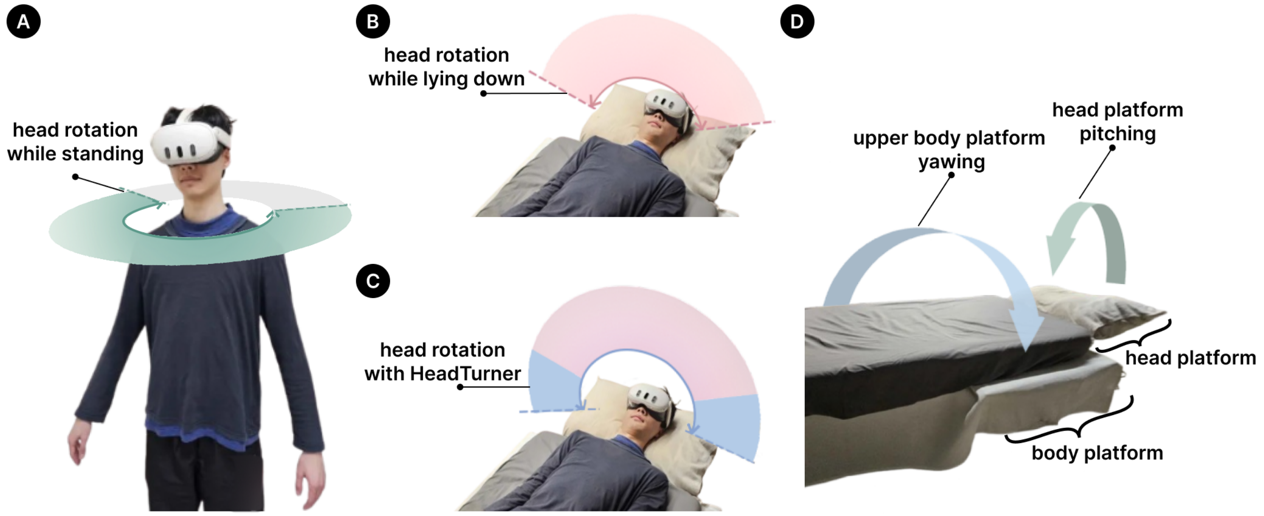

Figure 1: Viewing ranges using HMD under different conditions. Compared to (A) the Standing posture, a user can freely turn his head and body without physical constraints, while in (B) Lying Down, the head rotation range is reduced as the body movements are constrained by the bed. (C) We present HeadTurner, which extends the viewing range by assisting head-initiated upper-body movements. (D) The system provides 2-DoF actuation, including upper body yawing and head pitching.

Abstract

Virtual and mixed reality headsets, such as the Apple Vision Pro and Meta Quest, began supporting use in reclined postures in 2024, accommodating users who prefer or require this position. However,

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the surfaces on which users rest restrict shoulder and head rotation, reducing viewing range and comfort. A formative study (n=16) comparing usage while standing vs. lying down showed that head rotation range decreased from 261° to 130° horizontally and from 172° to 94.9° vertically. To improve viewing range and comfort, we present HeadTurner, a novel approach that assists user-initiated head rotations by actuating the resting surface to yield in pitch and yaw axes. In a user study (n=16), HeadTurner significantly expanded the field of view and improved comfort compared to a fixed surface. Although VR sickness was slightly reduced with HeadTurner, the difference was not statistically significant. Overall, HeadTurner was preferred by 75% of participants. Although our proof-of-concept device was prototyped as a bed, the approach can be extended to more compact and affordable device form factors, such as motorized reclining chairs, offering the potential for comfortable use of VR and MR headsets over extended periods , and was shown to inspire users with interested applications in back-rested scenarios.

CCS Concepts

• **Human-centered computing → Accessibility systems and tools**; *Interaction devices.*

Keywords

Head-mounted Display, Back-rest, Supine, Bed, Lying down, Ergonomic Movement, Upper Body Actuation, User Experience, Extended Viewing Range

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1 Introduction

Virtual and Mixed Reality (VR/MR) have introduced new visual and sensory experiences. As head-mounted displays (HMDs) freed humans from physical monitors and opened the vision for spatial computing with a larger viewing range. For example, the ultra-wide mode introduced by Apple Vision Pro [37] revolutionized the experience of immersive video [36] and productive app; Meta collaborated with Microsoft to convert one's home into a virtual office [18], all these major advancements happened in 2024, enabling abundant visual content to be showcased in the same room [34, 38].

The extended functionality and wearability imply broader long-term usage, making user comfort a crucial factor. However, associated head-turnings with wider visual content require more effort, especially in neck muscles [12, 78, 84, 85]. As people used HMDs in more supported scenarios such as in a reclined chair [2, 33] or on a bed for relaxation [16, 41], medical therapy [5, 52, 61, 65], regular apps for work, and gaming [8, 20, 21, 80].

However, the surfaces on which users rest physically restrict their shoulder and head rotation, reducing the viewing range and the comfort of head turning [57, 80] given that human central vision is as narrow as 5° [60]. Specifically, ultra-wide and multi-monitor modes expand to 172° (std=0.986°) and 151° (std=1.21°), respectively, while the suggested acceptable head rotation range in seated posture is 122°, and restrained within 90° to have moderate comfort [51] (The Vision Pro's angle is estimated with mirrored computer window maximized in ultra-wide mode [37]), and the Quest 3's angle is estimated with 3-window expanded [34, 35] in the default multi-monitor setting, both measured 10 times to calculate the average and standard deviation.)

To quantify how back-rested postures such as lying down affect viewing range, we conducted a formative study with 16 participants to compare the usage while standing vs. lying down. Results showed that the maximum head rotation range decreased by -50.2% horizontally (yaw) and -44.8% vertically (pitch). Specifically, the maximum rotation range decreased from 261° to 130° horizontally and from 172° to 94.9° vertically. Furthermore, the same angle of rotation of the head while lying down required significantly greater subjective effort and higher neck muscle activation vs. standing ($p<0.05$), as measured using surface electromyography (sEMG).

Although prior research has investigated techniques to expand the viewing range, including software approaches that rotate the virtual viewport [49, 50, 64, 69, 81] and hardware approaches that physically rotate users' bodies using external controller input [12, 26, 56, 75], these approaches create sensory conflicts and increased VR sickness [25] either due to visual-vestibular mismatch [43, 58] or self-environment disorientation [6, 44]. As a wider viewing range [54] and a reclined posture [58] potentially lead to higher sickness, supporting a comfortable viewing experience becomes challenging.

To improve viewing range and comfort for VR usage in back-rested postures, we present HeadTurner, a motorized 2-DoF platform that conforms to user-initiated head and shoulder rotations in the pitch and yaw directions, as shown in Figure 1. When users turn their heads to view content in VR/MR, the system rotates the bed and tilts the pillow to reduce the physical restrictions on the users' head and shoulders, which allows a larger rotation to expand the viewing range while keeping head supports to increase comfort.

We conducted a user experience study with 16 participants to evaluate the maximum viewing range and comfort, as well as VR usage experience. Results showed that the maximum viewing range increased by 24% horizontally and 9% vertically. To test user experience in both passive and active viewing, participants watched a hemisphere-view cinematic video and played a first-person shooter (FPS) game. Results showed that HeadTurner significantly expanded the head rotation range (20.3% in video, 12.4% in FPS, both $p<0.001$), improved comfort (both $p<0.03$), reduced subjective effort in FPS ($p<0.01$), with lower subjective ratings on the Fast Motion Sickness (FMS) scale (1.7 to 1.3 for video, 2 to 1.7 for FPS), though this difference was not statistically significant ($p=0.2$). Overall, HeadTurner was preferred by 75% of participants. Participants are also inspired of applications in back-rested scenarios including 4DX cinema [29, 48], virtual concert such as *VRChat* [68, 74], and 3D maneuvering just like in *Attack on Titan* [27, 79], in which users desire both comfortable viewing and engaged movements.

In summary, our key contributions include the following:

- Quantifying the reduced viewing range and comfort of VR/MR usage while lying down vs. standing to understand the experience of users who need or prefer to lie down.
- A novel dual-subsystem assistive approach to expand the viewing range and enhance the comfort of such VR/MR viewing experience, without causing VR sickness.
- The open-sourcing of HeadTurner[1]'s hardware and control software so that others can evolve and benefit from the system.

2 Related Work

With modern HMDs offering abundant visuals [38], such as the Vision Pro's ultra-wide display [9, 37], and the Meta Quest's expanded multi-monitor [18, 34], people started to use HMDs for daily tasks or gaming [8, 20, 21, 80] with lying down modes [4], in which viewing redirection enable back-rested postures like in a reclined chair or in a bed. More and more researchers have explored VR experiences in reclined and supine usage [57, 58, 80]. However, current research has not adequately addressed how physical support surfaces constrain users' shoulder and head rotation, despite this being a significant ergonomic challenge. Therefore, this section examines in the context of: 1) applications of HMDs in back-rested postures and their key challenges, with a focus on physical restrictions, as well as 2) existing solutions to address these issues. Through this systematic review, we aim to establish the foundational context for developing a novel ergonomic solution that minimizes the physical constraints imposed by support surfaces.

2.1 Existing HMD Applications and Issues in Back-rested Postures

The adoption of HMDs has been driven by both user interests and practical needs. For entertainment purposes, users have shown interest in VR experiences while in bed [80] with examples like 360° videos [15, 83] and gaming [21]. For practical usage, HMDs have been used to improve productivity with an expanded view [9, 20, 34]. In medical and healthcare applications, HMDs have been utilized for bed-bound patients to facilitate therapy [5, 40, 52, 53] or to collect neuropsychological assessments [23, 52, 76]. Following this trend, research began exploring the interaction challenges posed by supine HMD usage [80]. While current studies primarily focus on locomotion modalities [46, 57], there remained a significant gap in understanding the physical constraints that support surfaces impose on users during VR experiences. As pointed out in the paper "Towards a bedder future" [80], "In Bed, users often report feeling their head "anchored" to the pillow, with head movements (turning up and down, left and right) being particularly physically constrained in supine postures." Despite the qualitative head-turning issue mentioned, there is a lack of quantitative data from a human factors perspective, which motivated us to study and address head rotation constraints and the ergonomic burdens behind HMD usage in supine postures, as will be shown in the formative study.

2.2 Current Solutions to Improve Viewing Range of HMD Usage

We categorized previous work addressing the viewing experience of HMD usage into software and hardware solutions, each with distinct improvements and trade-offs in three key aspects: viewing range, effort of head-turning, and motion sickness. Software solutions have been developed to modify the mapping between physical and virtual head movements in immersive virtual reality (VR) environments. Continuous rotation approaches [49, 64, 81] used rotation gains to update the virtual view as the user's head turns, while discrete rotation approaches [64] snapped the virtual view only after the user's head turned past a certain angular threshold. GazeSphere [69] demonstrates navigating 3D videos in VR using head rotation and eye gaze, or using both to control VR viewports [50]. Although these software techniques enabled broader viewing in VR, they also induced sensory conflicts resulting from visual-vestibular mismatch and thus more motion sickness [25, 43, 44, 58].

Hardware solutions aimed to assist or augment the user's physical movements. Devices such as motorized beds and chairs [26, 56, 75] provided whole-body rotational support, reducing the effort of body-turning. However, their efficacy was limited when users were in reclined or supine postures, as the rotational axes did not align with the human spine, leading to unnatural posture transformations and self-environment disorientation [6, 44] and thus increased motion sickness [25, 43, 58]. Exoskeletons [12, 84] supported head movements by reducing the physical effort required, but the devices themselves were often bulky, and required clean space for the device, compromising the wearability of HMDs. Other haptic solutions include HangerOver [45] and Electrical Head Actuation [78], but they focus on problems like immersion and do not solve the physical constraints imposed by the backrest.

Our research seeks to bridge the gaps by quantitatively analyzing head-turning behaviors during supine HMD use and proposing a novel approach to address these challenges. We aim to improve the viewing range and comfort of HMD usage in back-rested postures, potentially expanding HMD applications and enhancing accessibility for a broader user base such as embedding the assistive features into motorized gaming chairs [2, 33, 56, 75].

3 Formative Study: Comparing Viewing Experiences using HMD while Standing vs. Lying Down

Our pilot study identified two main issues of using HMDs while lying down: 1) limited head rotation range and 2) increased effort. To identify these issues and assess their impact on user experience, we designed a formative study on using HMD while lying down compared to standing. We chose standing as the reference posture since body alignment is similar when standing and lying down [19] except for whether there is the support of a bed, previous research [80] further indicated that participants potentially had an illusion that they were standing in VR while lying down physically.

3.1 Apparatus

The bed for the study was set up using an IKEA BRUKSVARA mattress (80x200cm) and pillow (50x80cm), placed on a homemade

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[1] HeadTurner: https://github.com/ntu-hci-lab/HeadTurner

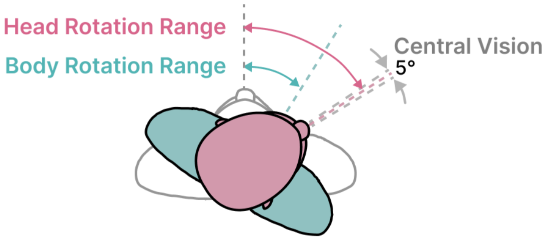

Figure 2: The definition of measured ranges of the head rotation and body rotation when a person looks toward the right. The baseline (gray line) is set as the facing direction when the head and body are not rotated. The head rotation and body rotation ranges are defined as the swept angle of the new head orientation (red line) and body orientation (green line), respectively, relative to the baseline. While the central vision of humans is about 5° [60].

frame, and Meta Quest 3 was used as the HMD. To ensure participants rotated in the correct direction, we developed a custom Unity application and used Meta Quest Link to display guiding tracks and text instructions within the headset.

3.2 Metrics

In the formative study, we measured four metrics: head rotation range, body rotation range, subjective effort of head-turning, and muscle contraction level.

The definitions of the measured head rotation range and body rotation range are illustrated in Figure 2. Head rotation angles were measured using Meta Quest 3's spatial data APIs. The body rotation angles were estimated using the OptiTrack motion capture system with six cameras [17], with six OptiTrack markers attached to the participant's chest using magnets. We chose the chest to represent the body rotation in the formative study because it is closer to the shoulder, which we expected to have the most rotation among all body parts during head-turning.

To estimate the subjective effort of head-turning, we adopted a 7-point Likert scale to rate participants' subjective effort, "How much effort is required to do the task?" — 1 (No effort required at all) to 7 (Maximum effort required), adapted from the 5-point Likert scale used to measure participants' physical demands [7], as the 7-point scale was found to have better resolution in our pilot study, and the 7-point scale maintains comparable study results with the 5-point scale during statistical analysis [10]. Additionally, 4 surface electromyography (sEMG) channels were attached to participants' necks to reflect their muscle contraction level, which served as an objective indicator of participants' effort and discomfort [55]. The sEMG channels were attached to participants' left/right sternocleidomastoid and splenius capitis muscles [85], with roughly 3 cm spacing between the electrodes. As shown in Figure 3 (C), the channels were connected through Grove sEMG detector modules driven by an Arduino Uno microcontroller board, which acquired the sEMG signals at a sampling frequency of 400 Hz.

Figure 3: Formative study apparatus and tasks. Participants performed head-turning tasks in 2 postures: (A) Standing posture and (B) Supine posture; (C) sEMG electrodes were attached to the neck's left/right sternocleidomastoid and splenius capitis muscles during head-turning tasks conducted in 8 directions horizontally, vertically, and diagonally.

3.3 Tasks and Procedure

Before the study, participants were introduced to the study and the HMD and performed neck warm-up exercises to ensure stable results and prevent injury [63].

In the study, 2 head-turning tasks were designed to measure our metrics, adapted from the study procedure [51] which measures participants' head rotation range and comfort when wearing HMDs by asking them to rotate their heads toward specified directions.

Participants performed 2 tasks in a fixed order:

- **T1 Maximum Range Head Turning**: This task aimed to investigate the maximum head rotation range. Participants were asked to rotate to the maximum range in 8 directions, 3 times each. The 8 directions were right, up-right, up, up-left, left, down-left, down, and down-right, as shown in Figure 3 (C).
- **T2 Fixed Range Head Turning**: This task aimed to explore the subjective and objective effort during head-turning. The maximum body rotation was also measured in this task since head rotation can be accompanied by body rotation [31], and we wanted to investigate whether the body rotation range is restricted while lying down, given the same fixed head rotation range. Before performing T2, OptiTrack markers and sEMG electrodes were attached to the participants. Participants were asked to rotate a fixed angle (30° for pitch, 50° for yaw, and 40° for diagonal directions) in the same 8 directions as in T1, 3 times each. After each direction, participants rated their subjective effort for that direction. Neck sEMG signals were recorded continuously during Task 2.

After both tasks were completed, we collected qualitative feedback about the perceived difference of head-turning between standing and lying down with semi-structured questionnaires.

The study adopted a within-subject design, in which each participant performed 2 tasks in standing and lying down postures. Standing posture required the participants to stand in a fixed position on the floor, and lying down posture required participants to lie flat on a fixed bed, as shown in Figure 3 (A) and (B). Therefore, each participant would perform 8 directions x 3 times x 2

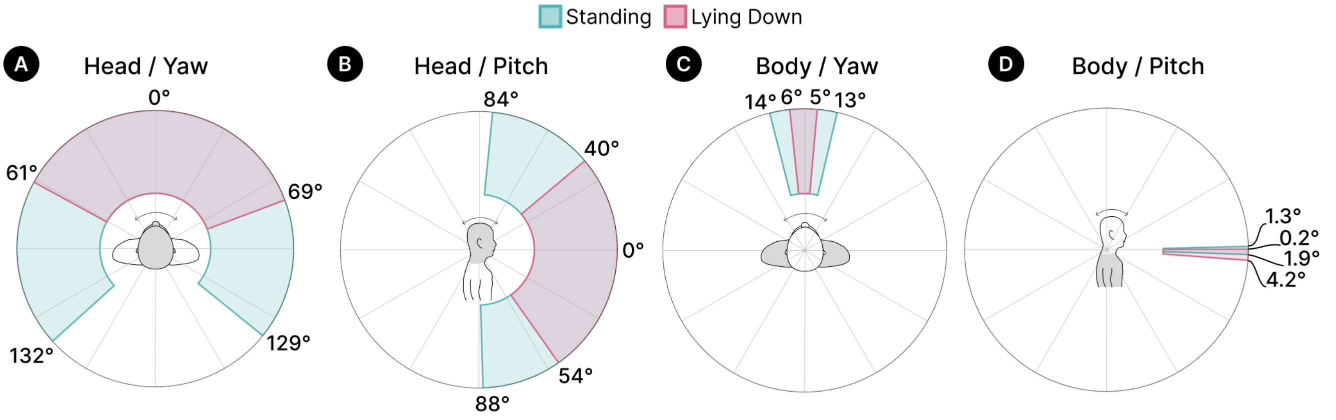

Figure 4: Participants' average maximum head rotation range in the maximum range head-turning task in (A) yaw and (B) pitch directions. And participants' average maximum body rotation range in the fixed range head-turning task while in (C) yaw and (D) pitch directions. All comparisons are between standing and lying down.

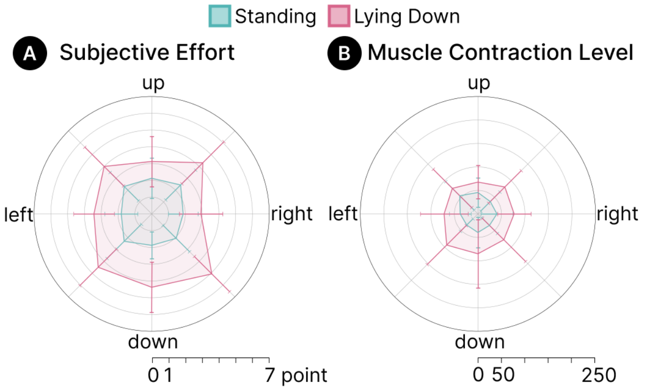

Figure 5: Participants' (A) average rating on the subjective effort during head-turning and (B) average muscle contraction level in 8 directions in the fixed range head-turning compared between standing and lying down posture. The error bars denote the standard deviation.

postures x 2 tasks = 96 head-turning trials. T1 and T2 were conducted sequentially, in which the order of directions and postures are counterbalanced through Latin Square. We asked participants whether they were tired at the end of each trial and let them rest until they could resume.

3.4 Participants

We recruited 16 participants (7 males and 9 females) aged 18- 31 years (mean = 23.4, SD = 3.58). One participant was left-handed, the others were right-handed, and 14 participants had HMD experience in the last few months. All participants were recruited through public forms posted on social platforms.

3.5 Quantitative Results and Discussions

Since yaw and pitch directions are the most common directions, below we mainly analyzed data from these directions. Complete data for the maximum head and body rotation range in all 8 directions are provided in Appendix A.

3.5.1 Maximum Range Head Turning: Maximum Head Rotation Range. As shown in Figure 4(A) and (B), the maximum head rotation range while lying down was reduced in all 8 directions. Specifically, the maximum head rotation range in yaw direction was reduced by 60° rightwards, 71° leftwards, 44° upwards, and 33° downwards. Wilcoxon signed-rank tests revealed that this reduction was significant in pitch down direction ($p < 0.01$) and all other directions ($p < 0.001$).

3.5.2 Fixed Range Head Turning: Comparing Body Rotation Range. As shown in Figure 4 (C) and (D), the body rotation range while lying down was reduced by 8° in both right and left directions, while in pitch directions the range was nearly the same as standing. Wilcoxon signed-rank tests revealed significant reductions in yaw right ($p < 0.01$) and yaw left ($p < 0.05$), while pitch-up and pitch-down movements showed no significant differences (both $p > 0.05$).

3.5.3 Fixed Range Head Turning: Subjective Effort Rating. As shown in Figure 5(A), participants' average rating of the effort required to turn while lying down increased compared to standing. Especially in downwards-related directions, which required a lot of core muscle exercise. Wilcoxon signed-rank tests revealed that the effort rating was significantly increased in all eight directions (all $p < 0.05$).

3.5.4 Fixed Range Head Turning: Objective Muscle Contraction Level. Regarding sEMG data, we first followed the processing method to transform raw sEMG data into muscle contraction level (MCL) presented in the paper "Toward Optimized VR/AR Ergonomics", as shown in Appendix B. We then analyzed the MCL data with Wilcoxon tests. As shown in Figure 5(B), participants' average MCL while lying down overall increased compared to standing, Wilcoxon signed-rank tests revealed that the muscle contraction levels were significantly increased for lying down posture compared to standing posture in six directions (all $p < 0.05$) except in up and up-left directions (both $p > 0.05$). These findings indicated that in these situations, participants' subjective effort ratings and their neck muscle contraction levels had consistent trends.

3.6 Qualitative Results and Discussions

Participants reported 4 main problems when turning while lying down:

3.6.1 Movement felt more restricted. : "It feels easy to get stuck when turning on the bed." (P2), "I feel my movement is more restricted when lying down" (P5), and "The range of whole body motion when lying down is relatively small, so are my head rotation angles." (P12)

3.6.2 Required more effort compared to standing. : "It is very tiring when turning my head while lying down, which requires a lot of effort." (P6), and "Overall, it requires more effort when lying down, especially in the up and down direction." (P7) Additionally, some participants also reported that they exerted more body parts in addition to neck muscles: "When lying down, my core muscles will exert more force." (P3), "It feels like more body muscles are used when lying down." (P9)

3.6.3 The friction of the pillow causes the headset to slip. : "Lying down is more physically demanding, mainly due to the friction of the pillow." (P8), "When lying down, I need to exert more force because the pillow drags my headset." (P11), and "I need to prevent the headset from slipping while lying down. It is difficult to find a resting position and I need to lift my head while turning to avoid the friction with the pillow." (P15)

3.6.4 The weight of HMD becomes more noticeable. : "When lying down, I feel like the headset presses on my forehead, making it more uncomfortable." (P10), and "When lying down, the headset is pressing against my face and nose, making my head feel heavier and harder to move." (P13)

While most of the participants gave negative feedback about turning while wearing an HMD in a lying-down posture, some participants said that they preferred a lying-down posture for relatively static HMD applications: "It might be good to watch a movie with HMD while lying down" (P7), "Generally speaking, I prefer standing, but if the scene is static and I don't need to turn, I prefer lying down." (P9)

To address these problems, we then focused our system design on increasing head and body rotation range, while reducing the effort required to turn with assistive actuations.

4 System Design

Based on the findings in the formative study, combined with design suggestions in previous work exploring supine postures [80], we focused on assisting and augmenting physical head rotations to facilitate visual-based experiences to enable effective interactions and maintain immersion. Our ultimate goal is to provide an extended viewing using HMDs that is comfortable and preferable in back-rested scenarios.

4.1 System Architecture and Components

We decomposed the whole system into 2 subsystems: 1) Head-following pillow to support pitching and reduce effort, and 2) Head-initiated body tilting to augment yawing and expand viewing range. The pillow lifting platform is connected via an axis fixed on the jig of the body platform, while the pillow actuator is grounded to the body platform by a designed 3D-printed holder. Two subsystems actuated independently and simultaneously, aligned with human joints to reduce self-environment disorientation [6, 44], avoiding motion sickness. Figure 6 shows the whole system architecture including head and body subsystems.

The head actuation subsystem consisted of an acrylic platform (600 mm width, 450 mm length), a pillow and motion tracker sealed on it, and a linear motor (Jiuying-NKLA87, 24V, 24W, 200N, 200 mm stroke, 60mm/s) installed with inclined 45° angle to the body platform actuated by L-298N Motor Driver will lift the platform to the commanded position implemented by tuned PID control with Arduino Uno and Hall-effect encoder, while the linear position and platform's rotary angle are converted using trigonometric functions. The head platform had a 60° rotation range with up to 15°/s turning rate. Ideally, we should support a maximum turning rate of human's central vision fixation [62, 70] up to 40°/s, while a previous work used 7.6°/s during their study to maintain 75% correct performance [70].

To support as many users as possible, the body platform is designed following the common practice in human-factored engineering [66] as considering the 5th percentile female to the 95th percentile male into design criterion, for example, the torso length (acromial height - crotch height) ranges from 549 mm to 628 mm according to NASA Anthropometric Source Book [1], the upper body platform is set as 600 mm length and 1000mm width under the bed mattress fixed to the DOF H2 motion platform, with a 50 mm margin from static lower body frame. The body platform could reach 23° of rotation with up to 86°/s turning rate.

4.2 Control Strategy

The diagram shown in Figure 7 illustrates the global closed-loop control. The Meta Quest 3 headset is connected to Unity, which could retrieve HMD's quaternion data to get HMD's viewing vectors. When the system initializes, there is a nearly 2-second (100 frames in unity) calibration phase reading and normalizing the user's head orientation in a rest state looking at the ceiling. Then unity program will use the head's pitch, yaw, and roll vectors to estimate the pitch and yaw angle. OptiTrack [17] is used to track the spatial data of HMD and head platform with high accuracy (1.3MP resolution, 4.2 ms latency) [11]. Both the tracked angles and control commands are filtered using exponential smoothing (alpha = 0.2) [32, 82]. The Arduino board and DOF box will autonomously drive their motors with local closed loops. As a whole, HeadTurner can adjust the body yaw and pillow pitch angles to accommodate users' posture transformations based on real-time head-turning.

For the body yawing command, the 23° angle of the body platform is linearly mapped to the ±45° head yawing angle. This mapping is based on the formative study indicating that the body yaw angle is approximately 27° during ±50° head yaw. As for the pillow's pitching command, the platform will be lifted when the head is leaving, and be lowered when the head is rotating towards it, as shown in Figure 8, where the control is realized by distance and angle hybrid sensing.

4.3 Technical Evaluation

4.3.1 Safety Considerations. Given that the operating range of HeadTurner is respectfully 60° and 23° in pitch and yaw direction,

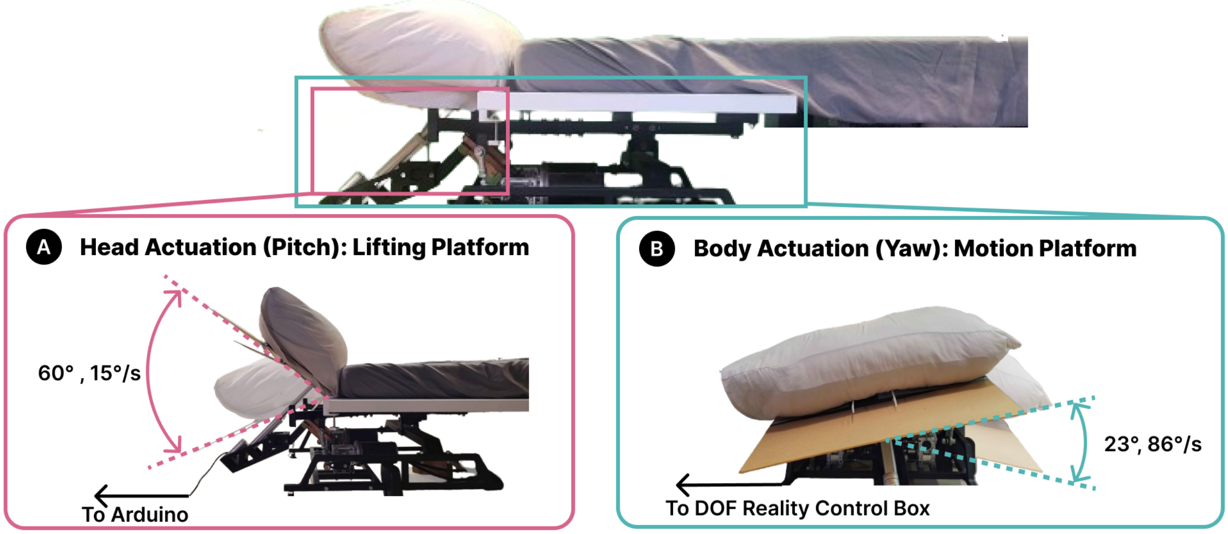

Figure 6: System architecture of HeadTurner. (A) Head actuation subsystem: a pitch angle controlled lifting platform is actuated by a linear motor; (B) Body actuation subsystem: a yaw angle controlled body platform (using DOF reality H2 model) is actuated with two rotational motors. The whole bed and head subsystem can be actuated simultaneously and provide independent yaw and pitch assistance as a whole.

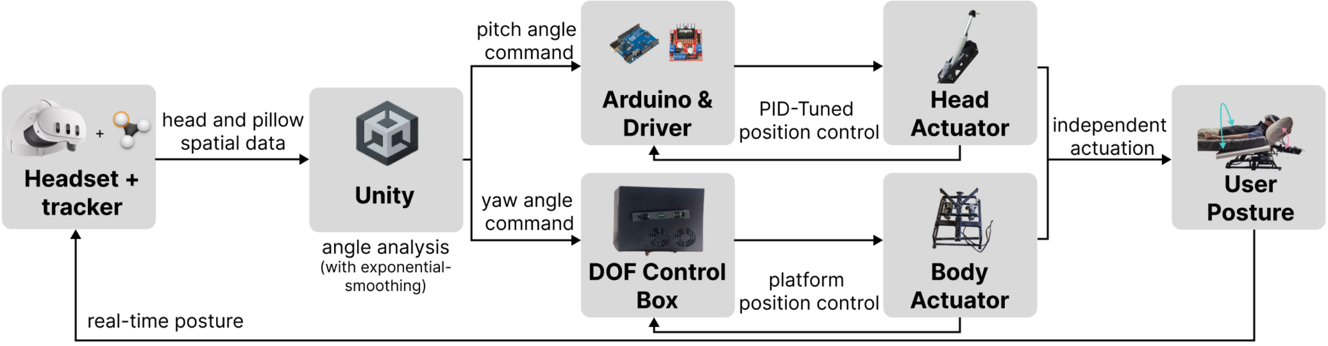

Figure 7: Control diagram of HeadTurner. The user's head orientation is sensed from head-mounted equipment like a headset or tracker, the spatial data is transmitted to the Unity program, and the angle control signal is then communicated to the Arduino board and DOF Reality's control box. The head subsystem and the body subsystem will act independently but cooperatively to assist the user's pitch and yaw movements to accommodate the user's real-time posture.

it is within human's normal turning range [51, 71]. For kinematic safety, the system's velocity and acceleration are considered based on human tolerance to impact while lying down [24] and measured as actuating the system between maximum range for 10 trials, recording the peak acceleration and velocity with a sampling rate of 50 Hz. According to Figure 9, our designed pitch velocity as 0.062-0.07 m/s is within the safe range of 24.38 m/s, and the pitch acceleration as 1.692-1.765 m/s² is within the safe range of 40G (392.4 m/s²). The yaw velocity of 0.5 m/s according motion platform's spec[72] is within the safe range of 9.144 m/s, and the yaw acceleration of 0.7G (6.867 m/s²) is within the safe range of 20G (196.2 m/s²). For fail-safeties, if the program is stopped accidentally, a reset command is delivered to both the actuator and motor, recovering the user's posture to a rest state. Were the communication or the power fail, the configuration of the closed-linkage mechanism will stay in its position which is within the anthropometric range of motion [71].

4.3.2 Responsiveness and Latency. To enhance the viewing range comfortably, the system should adjust in accordance to the user's movements, where typical head-pitching speeds during activities like locomotion can reach up to 33°/s [30], equivalent to 60° angle changed in 1.8 s, or 10° angle changed in 0.3 s. In the current prototype, when a new posture is given as in Figure 7, OptiTrack requires 4.2 ms [11] to gather and deliver the new spatial data

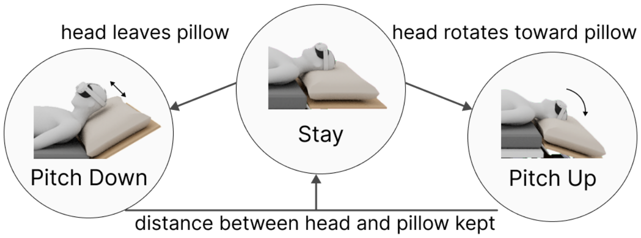

Figure 8: Pitch control method of HeadTurner. The distance between the head and pillow is detected via trackers on both the headset and head platform, which is used for pitch-down detection. The headset's quaternion data is used for detecting angle change in pitch-up direction, which can indicates the user's head rotation toward the pillow. Otherwise, the head platform will hold at any angle where the user's head stays.

to Unity, where the programs take 100 ms to analyze and deliver the commands toward Arduino and DOF Box. The pitch latency from the command received until the actuator position is reached depends on the target angle. Figure 10 shows that for different pitch angles (10° - 60°) in up/down directions, the response time for the subsystem is up to 3.335 s (std=0.07 s). While replacing the current linear motor with a stronger actuator could increase speed, it would also introduce challenges such as more noise, higher power consumption, and increased safety risks. For the yaw command, a maximum response time of 0.372 s is estimated according to the platform's spec[72].

4.3.3 Environmental Requirements. Regarding practical usage, the system's space, weight, and operational noise should be considered. Current HeadTurner occupies approximately 900mm x 2500mm x 500mm space and weighs around 40 kg. The maximum unloaded noise during operation is measured using a BENETECH GM1358 decibel meter (2 Hz sampling rate, 30-130 dB range) attached to the pillow, simulating the user's ear position. The system is commanded for maximum range movement at maximum speed and repeated for 10 trials. Dominated by the pitching actuator, the maximum noise vs. pitch direction is shown in Figure 9, with a base ambient level of 51dB and 65.65dB maximum during pitching down. According to the Decibel Level Comparison Chart [28], 60-70dB is equivalent to "Normal conversation".

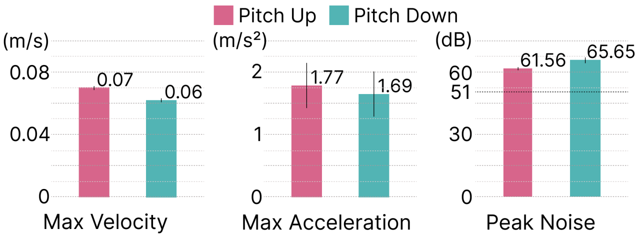

Figure 9: Technical evaluation details and measurement for pitch subsystem, including max velocity, max acceleration, and peak noise. The ambient noise level of 51 dB is shown as the dashed baseline. (N = 10)

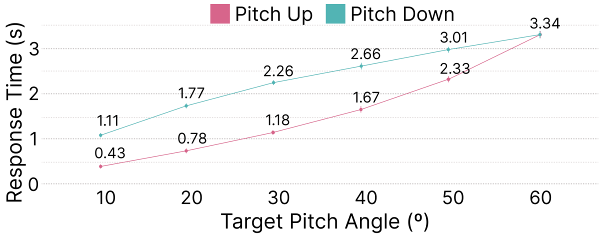

Figure 10: Response time corresponding to different target pitch angles. Including the latency of data gathering and processing (104.2 ms)

5 Summative Study: Evaluating User Experience of with vs. without HeadTurner while Lying Down

To assess whether HeadTurner improves the viewing range and comfort while lying down, we first measured participants' maximum head rotation range as in the formative study, in the condition of lying down with and without HeadTurner. Next, to validate whether HeadTurner enhances user experience in free-play applications including passive and active viewing, a hemisphere-view cinematic video and an FPS game were tested under both conditions and measured metrics including effort, sickness, comfort, and preference.

5.1 Application

Two commercial applications were chosen as the validation scenarios with Meta's lying down mode, Ecosphere[2] was a relatively static application but with plentiful visual content similar to National Geographic and 5.7K high-resolution filling the full frontal field of view as shown in Figure 11(A) and (B), while HyperDash[3] encouraged more movements and spotting in the FPS game field. For video, the timestamps are controlled to have a consistent experience across participants, and we selected two episodes for participants to experience with and without the HeadTurner system, employing a counterbalanced design. For the FPS game, the experience is controlled including difficulty, game scene, weapons, and the enemies and player's teammates are auto-respawned.

5.2 Metrics

In the summative study, we included the 4 metrics from the formative study: head rotation range, body rotation range, subjective effort, and muscle contraction level of head-turning, and adopted 3 more user experience metrics for the free-play scenario including VR sickness, comfort, and overall preference.

The measurement methods followed the formative study. However, the body tracker was moved from the chest to the abdomen because in the formative study, we observed that the device might be affected by the participant's chest shape, leading to instability. We also noticed in the formative study that participants rotated

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[2] Ecosphere's official website: https://www.phoria.com.au/projects/ecosphere/. Until August 2024, Ecosphere had a 4-star rating and 175k downloads.

[3] HyperDash's official website: https://www.hyperdashvr.com/. Until September 2024, HyperDash had a 4.5(3.1k) rating on the Meta app store.

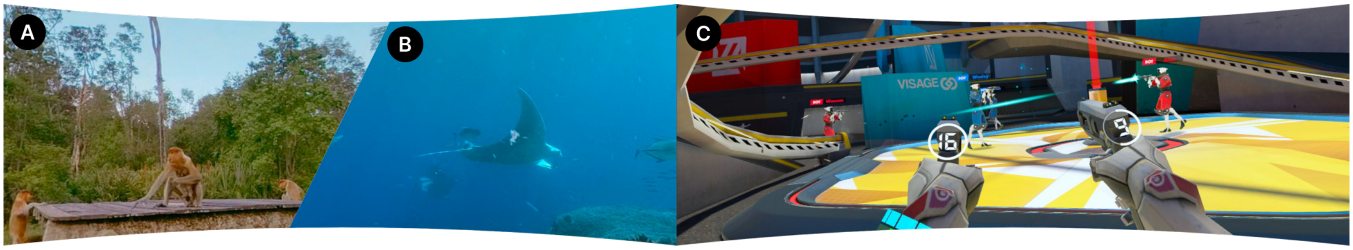

Figure 11: Application scenes in the summative study. In Ecosphere's hemispherical videos, participants experienced two episodes as (A) Borneo-03 and (B) Raja Ampat-04 in a counterbalanced order, whereas in (C) HyperDash's FPS game, participants with random-generated teammates and enemies are battled within a specified region.

their upper bodies as a whole during the rotation process, so relocating the device to the abdomen did not affect the representativeness of the measurement results.

As for possible VR sickness during head-turning, we adopted a 10-point Fast-Motion Sickness (FMS) scale, "How sick is the experience?" — 0 (No sickness at all) to 10 (Severe sickness) [42, 73]. In order to unify the scale of each question, the question to measure subjective effort in the formative study was re-mapped to 10 points: "How much effort is required to do the task?" — 0 (No effort required at all) to 10 (Maximum effort required). Participants also rated their subjective comfort and preference by first choosing a preferred feedback type then rating the degree of difference on a 5-point scale, then mapped to 10-point during analysis [14].

5.3 Tasks and Procedure

The summative study adopted a within-subject design consisting of two tasks. Throughout the study, participants wore sEMG and OptiTrack trackers. The first task was the maximum range head-turning task in the formative study, but the measured turning directions were reduced from 8 to 4 (only yaw and pitch). The second task was free-play scenarios, where participants experienced two hemispherical videos in Ecosphere, presented in a counterbalanced order, and an FPS game in HyperDash twice with the same setting, both under the conditions with and without HeadTurner and counterbalanced. After completing both tasks, we collected participants' qualitative feedback on their perceived differences in head-turning with and without HeadTurner, using semi-structured interviews enriched by the co-speculation method [13].

5.4 Participants

We recruited 16 participants (7 males and 9 females) aged 18 - 41 years (mean = 24.6, SD = 8.1). Two participants were left-handed, the others were right-handed, and 12 participants had HMD experience in the last few months. All participants were recruited through public forms posted on social platforms.

5.5 Quantitative Results and Discussion

5.5.1 Maximum Range Head Turning: Maximum Head and Body Rotation Range. As shown in Figure 12(A) and (B), the maximum head rotation range with HeadTurner increased in all directions. Specifically, the maximum head rotation range increased by 13° rightwards and 17° leftwards. Wilcoxon signed-rank tests revealed that this increase was significant in the yaw directions ($p < 0.01$), while the results were insignificant in the pitch directions. The insignificance in pitch-up direction reflected the design that the head-following pillow was to provide adaptive support, but not affect the actual angle turned. Moreover, the maximum body rotation range was increased by 12° rightwards and 12° leftwards ($p < 0.001$) as shown in Figure 12(C).

5.5.2 Free-play Scenarios: Rotation Range Expansion with Muscle Contraction Level Reduction. Investigating the cumulative distribution function in Figure 13, the turned angle (directionless, relative to the rest position) during FreePlay was significantly expanded (both $p<0.001$) by 20.3% (Ecosphere) and 12.4% (HyperDash), revealed by the Kolmogorov-Smirnov test [59]. Among 90% of the time, the turned angle stayed within about 75°, in this region, the average muscle contraction level is also reduced with HeadTurner in both applications as shown in Figure 14, except for the small angle region in FPS game, possibly due to the behavior of more frequent head turning near the rest position encouraged by HeadTurner instead of just resting on the pillow.

5.5.3 Free-play Scenarios: Subjective Effort and VR Sickness. As shown in Figure 15, overall the participants' subjective effort with HeadTurner decreased, especially in FPS game by 1.4 ($p < 0.01$), while the average sickness decreased by 0.4, but with no significance ($p=0.2$).

5.5.4 Free-play Scenarios: Comfort and Preference Improvements. As shown in Figure 16, HeadTurner significantly improved comfort ($p<0.03$) in both video and FPS and preferred ($p<0.01$) in video. Overall, 12 out of 16 participants preferred HeadTurner in lying down usage.

5.6 Qualitative Results and Discussions

To get enriched feedback not only about the perceived difference with and without HeadTurner, we spiced the semi-structured interview with open questions like "What were the most surprising, confusing, or impressing moments during your experience?", as a co-speculation method utilized in situated design [13] to see users' inspiration about future applications where they were in back-rested scenarios besides lying down.

5.6.1 The effect of improved viewing range. By assisting the user to explore more content in the scene, the satisfaction and performance during the application were enhanced (P11, FPS):

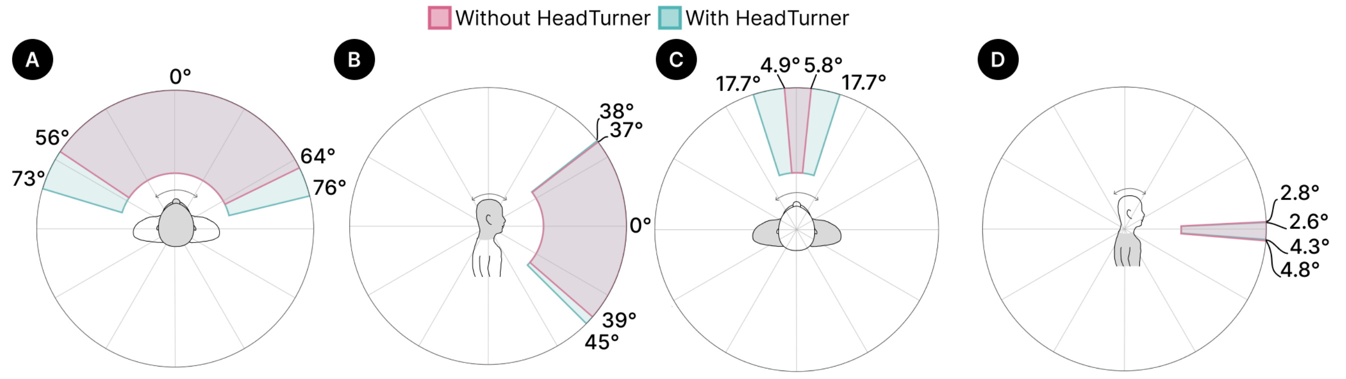

Figure 12: Participants' average maximum head rotation range in the maximum range head-turning task in (A) yaw and (B) pitch directions. And participants' average maximum body rotation range in the fixed range head-turning task while in (C) yaw and (D) pitch directions. All comparisons are between the HeadTurner turned off (normal bed) and turned on.

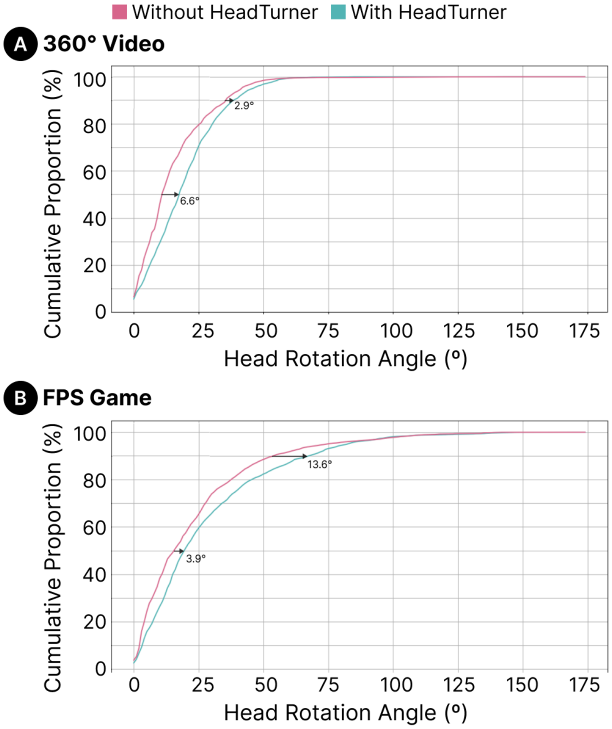

Figure 13: The cumulative distribution function of the head turned angle during free-play applications including the 360° video and the FPS game. Overall the turned angle with HeadTurner is expanded in both applications as shown with the right shifts in the 50th and 90th percentile.

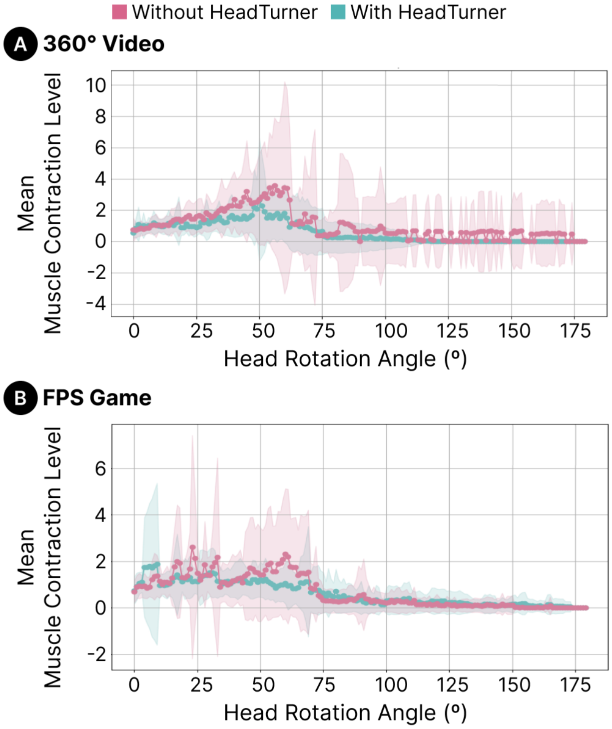

Figure 14: The muscle contraction level (MCL) versus head turned angle during free-play applications including the 360° video and the FPS game. Overall the MCL with HeadTurner is reduced across all turned angle ranges in the 360° video, and reduced in most ranges in the FPS game except in the small angle region. The MCL value is plotted with a 1° window size.

> "The wider viewing range let me see more roads in the FPS game, spotting enemies more easily, and thus shooting more effectively."

5.6.2 The effect beyond viewing range. Although not targeting immersion and realism, when asking about their experience difference, 5 of 16 users reported that the HeadTurner made the experience more immersed, real, or natural (P1, Video):

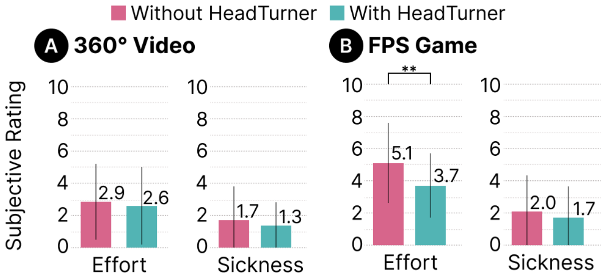

Figure 15: Participants' average rating of subjective effort and perceived fast motion sickness (FMS) when (A) watching 360° videos and (B) playing FPS game.

> "I felt more immersed—not just watching with my eyes, but engaging with my whole body. The 3D video felt much closer than a 2D one, and I could move my head and body to follow the animals, making it feel incredibly real, as if I were truly part of the virtual world. It was so comfortable that I forgot I was lying in bed; it felt just like sitting or standing. One of the most touching moments was turning my head to watch the sunrise and looking down as a tree fell from a bird's-eye view."

5.6.3 Unexpected benefits of embodied actuation. We included the dizziness rating in the summative study due to the motion sickness concern, but it turns out that the dizziness is somewhat reduced in more active applications (P4, FPS, the participant is the most active one who rolled back and forth on the bed during the FPS):

> "Before I was asked to play the FPS on the Bed, I expected the rotatable bed would make me ill, but surprisingly it felt like reducing the dizziness! I'm so confused with that feeling, maybe it is because I'm moving a lot myself? (compared to the video watching)"

5.6.4 Physical turning versus controller snapping. To facilitate normal gameplay, we also taught the participants to use the built-in controller snapping in the FPS if they preferred. After that, some participants expressed that physical head turning is more intuitive than virtual display snapping, where not only the physical effort but also the mental load might be affected (P9, FPS):

> "When using a joystick, it took me some time to realize the transformation and redirect myself in the scene, which increases my mental effort, and makes me feel less agile in the game."

We post-explored that such visual redirections may cause discomfort due to vergence-accommodation (VA) conflict [47].

5.6.5 However, the assistive features of the system are not catering to everyone. Some participants said that they prefer a more active actuation instead of self-initiation (P11, Video):

> "I had to move my body first for the bed to turn. Although the speed was smooth and appropriate, the bed felt less responsive to small movements. When watching videos, compared to gaming, I tend to be more relaxed and prefer not to move myself as much. It would be beneficial if the bed could actively turn to where I want to look, even without requiring neck movements."

And some of the participants wonder why a bed should move (P4, FPS):

> "Normally, I think the bed is not meant to move, if I'm playing games that require much movement, I just prefer to play it off the bed."

Additionally, the pillow following speed is the limitation of the current version of the system (P4):

> "The return speed is slow, sometimes I have turned to the position that I want to look at, and the bed turns making my view deviate."

though some participants had different acceptance of speed (P11):

> "I feel more free and unrestrained with the actuated bed, however, I think it turned too fast."

5.6.6 Overall, HeadTurner pioneers the future of using HMD in more comfortable or rest postures for plentiful visuals. As a experience comparison, HeadTurner potentially supports the long-term usage of HMDs (P3):

> "When using an HMD on a regular bed, I usually reach my limit after about 10 to 20 minutes due to tiredness and fatigue. However, with the actuated bed, I feel like I could comfortably continue for another 10 minutes without any issues."

Although the preference of actuated or non-actuated is still open to debate, HeadTurner opened up a new option for those seeking a more comfortable working environment for long-term usages (P6, a VR artist):

> "There still isn't a clear choice... Ideally, I'd like it to be selectable so I can try it out myself. As an artist, I often create vehicle models in VR, and using an HMD while sitting or standing can become exhausting after long hours of work. I usually rest on my bed while modeling at home, so with a transformable bed like this, I'd be interested in trying it for my workflow."

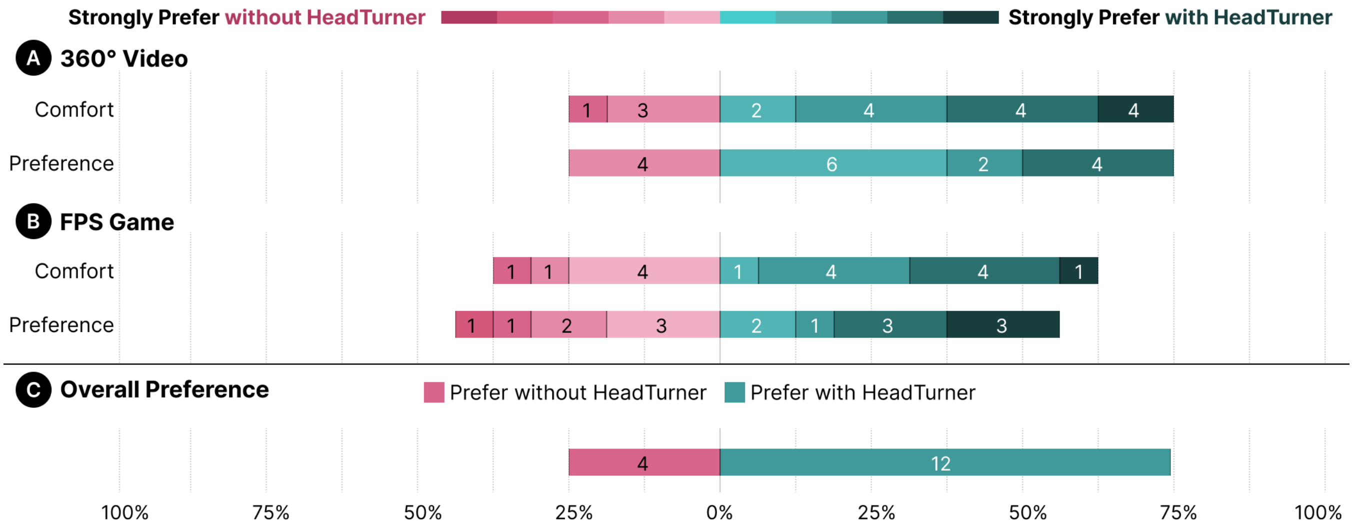

Figure 16: Participants' user experience ratings comparing conditions without and with HeadTurner for two tasks: (A) watching 360° videos and (B) playing an FPS game. Participants significantly rated HeadTurner higher in both comfort and overall preference across both tasks.

and the effort-saving and motion-augmenting feature potentially helps those with less mobility (P6):

> "It will be beneficial for the disabled, when constrained to the home on the bed, only the ceiling and walls can be seen, the VR can enable them to explore more worlds outside. Moreover, the neck-relieving feature is good for those patients with fewer exertions."

5.6.7 Inspired Applications. With the co-speculation methods [13], participants showed interests beyond passive applications like 4DX cinema (P7) but also for those more engaging ones like virtual concert [39] (P13):

> "I'm impressed that a bed can move, which is suitable for interactive VR scenes such as *VRChat*, where I want to cheer for multiple dancers on the wide stage, and sometimes I would look at the people beside me and wobble with the music rhythm (a little shy), an actuated bed give great support for that."

and even more intensive games like 3D maneuvering as in *Attack on Titan* [79] (P16):

> "This device provides a sense of suspension…like watching videos in space or underwater, feels like I can play with more motion-required games safely. For example, when the *Attack on Titan* was advertised, people jokingly called it a 3D motion sickness simulator because the game often includes extensive visual shaking or wide-range rotation, which easily makes one sick even when just watching the preview video. Also, performing dodge moves while standing in VR is dangerous. If a device like this could be adapted into a gaming chair that adjusts and supports body movements, it would be very impressive."

In summary, HeadTurner can be further developed to switch between chair (sitting) and bed (lying) modes, serving motion accommodations so that users can explore the visuals HMDs provide comfortably.

6 Discussion and Future Work

6.1 Trade-offs between Support and Freedom of Movement

The balance between support and freedom of movement is an important design consideration for supportive furniture. For instance, a spring bed offers more support compared to a bean bag sofa, but it also restricts movement due to its limited ability to adjust its shape. HeadTurner combines the advantages of both, providing greater freedom of movement than traditional bedding or seating but keeping supports. Its actuation capability reduces the effort during posture adjustments, enabling realistic embodied interactions—key for immersive virtual reality experiences [22]. By addressing both support and freedom of movement, HeadTurner overcomes the limitations of traditional furniture as seen in the summative study.

6.2 Potential for Accessibility

Beyond alleviating movement restrictions caused by the support surface, HeadTurner can benefit individuals with physical disabilities in performing movements, as over 15 million people worldwide live with spinal cord injuries [67]. By employing a mechanism that uses head movements to simulate full-body rotation as if standing, HeadTurner has the potential to assist these individuals like in wheelchairs [77] to engage VR experiences while promoting movements of those with less mobility [3].

6.3 Assistive versus Active Control

HeadTurner utilized the inversion of control principle, where user motion triggers associated actuation, but not the actuation leads to user motion. Such an embodied approach prevents potential sickness and is also essential to improve user agency, however, some users showed interest in a more active approach, where they preferred the system to actuate on behalf of themselves, in such a scenario, the prediction of user intention is critical to avoid sensory conflict, where the system may integrate the gaze-tracking sensing [50] to achieve high responsiveness, and hybridized with the head orientation sensing to maintain stability.

6.4 System Costs and Evolutions

As a proof-of-concept prototype, HeadTurner is currently implemented using an optical tracking system costing $2,199 and a motion platform of $ 1,950. However, these components could be replaced in the future to reduce costs. For example, the 2-DoF motion platform could be substituted with the 1-DoF one, and the optical tracking system could be replaced by VR trackers or the gyroscope within the headset, significantly lowering expenses while preserving core functionality. Building on the design principles of HeadTurner, next-generation motorized gaming chairs [2, 33, 56, 75] could incorporate a mechanism to enable natural body rotation, enhancing users' viewing range and immersion in VR.

Including motorized hardware, HeadTurner is a user-initiated system yet is capable of providing haptic feedback. Future research combining extended viewing ranges with enhanced haptic feedback could further enhance the system's value and the user experience.

6.5 Demographic Limitations

Although the formative study involved 16 participants, the demographic range was not sufficiently diverse to draw conclusions about its applicability to individuals with disabilities or older adults. Future studies involving a more diverse user base could provide valuable feedback to guide further development tailored to specific groups.

7 Conclusion

We presented HeadTurner, a motorized platform designed to improve viewing range and comfort in VR/MR while lying down. It supported shoulder and head movement by simulating their rotation as if standing, based on insights and the ratio of head and shoulder rotation from our formative study. Comparative user studies in VR applications demonstrated that HeadTurner significantly enhanced viewing range and comfort, was preferred by participants, and reduced VR sickness vs. normal bed. Furthermore, our comparison of viewing range and effort between lying down and standing offers valuable insights for ergonomic designers. To support further research and development, we have open-sourced both the hardware and software of HeadTurner.

Acknowledgments

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A Formative Study Resultant Data

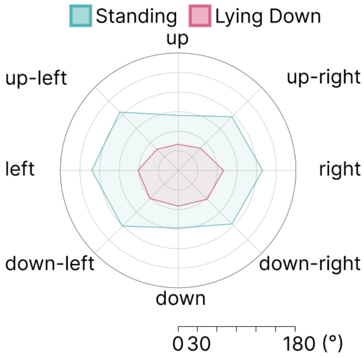

Figure 17: Participants' average maximum head rotation range in the maximum range head-turning task in all eight testing directions.

Table 1: Mean and standard deviation of maximum head rotation range at 2 posture x 8 directions

Direction	Maximum Head Rotation Range			
	Standing		Lying Down	
	Mean	SD	Mean	SD
right	129.07	44.25	69.42	33.85
up-right	116.21	47.58	46.12	21.38
up	84.32	22.37	40.06	16.9
up-left	126.2	47.01	45.75	15.85
left	132.1	46.39	61.26	20.42
down-left	120.81	55.62	61.03	23.56
down	88.31	36.51	54.87	43.79
down-right	116.33	48.86	62.6	30.57

Table 2: Mean and standard deviation of subjective effort score at 2 posture x 8 directions

Direction	Effort Score			
	Standing		Lying Down	
	Mean	SD	Mean	SD
right	1.88	0.89	2.94	1.29
up-right	2.44	1.26	4.31	1.78
up	2.13	1.2	3.13	1.5
up-left	2.31	1.2	4.0	1.63
left	1.81	0.98	3.44	1.21
down-left	2.31	1.45	4.5	1.55
down	1.88	0.81	4.38	1.5
down-right	2.06	1.12	5.06	1.48

B EMG to Muscle Contraction Level Pipeline

Following the EMG to Muscle Contraction Level (MCL) pipeline shown in the paper "Toward Optimized VR/AR Ergonomics: Modeling and Predicting User Neck Muscle Contraction", we processed and transformed our collected 4-channel raw EMG signals (2D-data) into overall neck muscle contraction levels (1D data). Our complete algorithm is shown in Algorithm 1.

Algorithm 1: EMG to MCL Data Processing Pipeline

```
Input: EMG
Output: Channel-wise sum of processed EMG
Function EMG2MCL(EMG):
    // 4-channel EMG signals
    $t \leftarrow$ GetTimestamps(EMG) // EMG timestamps
    AXIS $\leftarrow$ 0;
    BANDPASS_FREQ_LOW $\leftarrow$ 20 Hz;
    BANDPASS_FREQ_HIGH $\leftarrow$ 150 Hz;
    LOWPASS_FREQ $\leftarrow$ 1 Hz;
    BUTTERWORTH_ORDER $\leftarrow$ 4;
    // Constant detrending
    EMG $\leftarrow$ EMG $-$ Mean(EMG, AXIS);
    // 4th order Butterworth bandpass filter
    SAMPLING_RATE $\leftarrow$ Len(EMG)$/(t[-1] - t[0])$;
    LOW $\leftarrow$
      $(2 *$ BANDPASS_FREQ_LOW$)/$SAMPLING_RATE;
    HIGH $\leftarrow$
      $(2 *$ BANDPASS_FREQ_HIGH$)/$SAMPLING_RATE;
    EMG $\leftarrow$ sos_bp(EMG, ORDER, [LOW, HIGH], AXIS);
    // RMS envelope filter
    WINDOW $\leftarrow [1/1000, \ldots, 1/1000]$ // 1000-length
    for $i \leftarrow 0$ to 3 do
        EMG$[i] \leftarrow \sqrt{\text{CONV(EMG}[i]^2\text{, WINDOW)}}$;
    end
    // 1st order Butterworth lowpass filter
    LOW $\leftarrow (2 *$ LOWPASS_FREQ$)/$SAMPLING_RATE;
    EMG $\leftarrow$ sos_lp(EMG, ORDER, LOW, AXIS);
    // Compute overall MCL
    AXIS $\leftarrow$ 1;
    return sum(EMG, AXIS) // Channel-wise sum
```