Characterizing the Effects of Adding Virtual and Augmented Reality in Robot-Assisted Training

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Abstract—Virtual reality (VR) and augmented reality (AR) are emerging technologies in rehabilitation and have the potential to be combined with robot-assisted training (RAT). In this study, we investigate the effects of adding VR and AR into sitting posture training involving a robotic Trunk Support Trainer (TruST). Sixty-three healthy subjects were randomly assigned to three groups: physical reality group (PR group), AR group, and VR group. During training, subjects practice multidirectional reach tasks with robotic assistance provided by TruST. Reach targets were real in the PR group but virtual in the AR and VR groups. Training environments were real in the PR and AR groups, but virtual in the VR group. Before and after training, all subjects underwent a functional reach test to measure changes in motor performance, gains in workspace area and postural control flexibility. Additionally, they completed five standard questionnaires assessing presence, immersion, simulator sickness, engagement, and enjoyment. Our results indicate that both VR and AR significantly enhanced the effectiveness of TruST-assisted training. However, the VR group experienced a higher simulator sickness compared to the AR group. This comparative study sheds light on the added value of VR and AR in RAT and should serve as a stepping stone for the development of novel XR-enhanced RAT platforms and paradigms for training.

I. INTRODUCTION

Dynamic postural control during sitting requires maintaining balance during voluntary and involuntary movements. This ability may be impaired in people with neuromotor disorders such as in spinal cord injury and cerebral palsy, which challenges them in performing daily activities [1].

Conventional training (CT) strategies, such as muscle strengthening, joint locking, and proprioceptive training, are known to improve sitting posture control [2]. However, providing sufficiently rich intervention in CT can be labor-intensive and expensive [3], [4]. Additionally, simple repetitive movements involved in CT may not be stimulating for patients, leading to a lack of enthusiasm to continue the treatment [5], [6]. Therefore, novel technologies are being explored to overcome these limitations.

Robot-assisted training (RAT) is an emerging technology for posture control recovery that provides several benefits over CT, such as standardized training environments, adaptable supports, increased intervention intensity, and reduced physical burden on therapists [7]. We have developed a cable-driven robotic rehabilitation platform, Trunk Support Trainer (TruST), that can apply force to the trunk [8]. During training, subjects practice multidirectional reach tasks while receiving assistive forces at the trunk as they move their trunk beyond the stability limits. Our previous work reveals that TruST-intervention could effectively expand the sitting workspace and improve motor performance for cerebral palsy and spinal cord injury patients [9], [10].

Virtual reality (VR) and augmented reality (AR) are also gaining popularity in posture training [11], [12]. VR immerses subjects into a 3D rendered virtual environment, while AR superimposes virtual items in the physical real world [13]. Current researchers view VR and AR as the same technology but with different levels of immersion, merging physical reality and virtuality, represented as two points on a reality-virtuality (RV) continuum [14]. As shown in Fig. 1, VR and AR sit close to the right end of the spectrum (absolute virtual environment [15]) and left end (physical reality) on the continuum, respectively. Broadly, the spectrum can be labeled as extended reality (XR) [16]. Several studies demonstrate that the inherent gamification property of VR and AR could enhance enjoyment and encourage voluntary participation, thus increasing intensity and training outcomes [17], [18]. Further investigations indicate that VR and AR could accelerate motor learning by triggering neurophysiological changes and stimulating neural plasticity [19]–[21].

Recent studies seek to combine RAT with VR or AR to further improve motor recovery [22]. Manuli et al. [23] and Calabro et al. [24], [25] applied VR to the Lokomat robotic platform to assist gait training. Patients who received VR-enhanced RAT showed more significant improvements in cognitive recovery and motor control than those who took CT. Saleh et al. [26] and Comani et al. [27] introduced VR to upper limb RAT and found neural pattern reorganization in stroke patients during the intervention. Crignis et al. combined AR game with a serial link manipulator to develop an AR-enhanced RAT system, which was highly rated for its usability and feasibility by both patients and therapists [28].

Despite these promising results, it is still being determined whether combining RAT with XR, primarily VR and AR, is
more effective than using RAT alone [29], [30]. Numerous virtual objects presented in XR could cause cognitive overload and distract patients from RAT tasks [22], [28], [31]. Furthermore, immersive virtual environments isolate patients from real RAT environments, which might impair their communication with therapists and pose safety risks due to their reduced awareness of reality [32]. On the other hand, as the immersion level of XR increases, so does user enjoyment and engagement, which may enhance the intensity and efficiency of RAT [20]. However, higher immersion also poses a higher risk of simulator sickness, manifested as nausea, dizziness, and eye fatigue [32]. These symptoms could be exacerbated by frequent and rapid head movements that are typical in RAT. Therefore, it is also worth investigating whether VR or AR is more effective when combined with RAT.

To expand potential clinical applications and the impact on patients, Zanatta et al. [29] suggested that more random control trials should be conducted to further investigate the effects of applying XR to RAT. In this paper, we performed a comparative study by integrating VR and AR into the TruST robotic platform. Sixty-three healthy subjects were randomly assigned to three equal groups: physical reality group (PR group), augmented reality group (AR group), and virtual reality group (VR group). During training, each subject completed 12 rounds of multidirectional reach tasks with assistance provided by TruST. Reaching targets were real in the PR group but virtual in the AR and VR groups. Training environments were real in the PR and AR groups, but virtual in the VR group. Before and after training, all subjects performed a functional reach test. Their motion and underseat pressure data were collected to analyze motor performance, workspace area, and posture flexibility. They were also asked to fill out five standard questionnaires to measure the presence and immersion level, simulator sickness level, engagement, and enjoyment. Our results revealed that both VR and AR could significantly improve the training effects of the TruST intervention. When combined with RAT, VR performed equally well as AR. However, the VR group exhibited a higher level of simulator sickness than the AR and PR groups. This study helps better understand the added value of integrating VR and AR into RAT and should serve as a stepping stone to promote the development of novel XR-enhanced RAT platforms and interventions.

II. METHODOLOGY

A. Subjects

Sixty-three healthy subjects participated in this study (age = 17 ∼ 51; females = 27; left-handed = 4; mean height = 171.3 ± SE = 5.1 cm and mean weight = 67.4 ± SE = 10.4 kg). Approval for all ethical and experimental procedures in this paper was sought and granted by the Institutional Review Board (IRB) of Columbia University under Protocol No. AAAR7781. Informed consent was received from all human subjects. The IRB approval date was 10/11/2023.

B. Robotic Platform and XR Devices

As shown in Fig. 2, TruST is a cable-driven RAT platform. Four cables are attached to a belt at the trunk. Four motors (Maxon Motor, Switzerland) instrumented with load-cells (LSB302 Futek, CA) are mounted on a stationary frame to control the cable tensions. Motion capture cameras (Vicon Vero 2.2, Denver) provide real-time position and orientation of the belt to the robotic controller. When the estimated trunk center (pink point in Fig. 2) moves beyond the sitting stability boundary, TruST applies an assistive force (blue arrow in Fig. 2) to help subjects maintain balance. Details of the TruST control mechanism are described in our previous work [8].

Two flagship XR head mounted devices (HMDs) available on the market, Microsoft HoloLens 2 (Fig. 3a) and Meta Quest Pro (Fig. 3b), were used to deliver AR and VR experiences to subjects in this study, respectively. Both devices were determined to be usable, reliable, and effective in rehabilitation [33], [34]. Unity3D Engine (version 2021.3.21f1) and the MRTK3 package (Microsoft, WA) were used for the development of custom XR game application and cross-platform deployment. The application is available to the research community upon request consistent with the IRB guidelines (Unity project access link: https://roar.me.columbia.edu/content/trust).

C. Experiment Setup

The schematic diagram of the study design is shown in Fig. 3. The experiment consists of three stages: baseline test session, training session, and post-training test session.

Before training, a postural star sitting test (PSST) was performed [35]. Subjects wore a trunk belt and sat in the TruST without foot support. Cables were removed from the belt. Subjects were instructed to reach in eight principal directions. They used the dominant arm for the directions: front (F), front-dominant (FD), dominant (D), back-dominant (BD), and back (B); and the nondominant arm for the remaining three directions: front-nondominant (FND), nondominant (ND), and back-nondominant (BND). Before each reach, subjects sat upright and extended the arm to 90 degrees of shoulder flexion. Then, they were instructed to reach as far as possible without losing balance. The distance between their start and farthest reaching positions of the index fingertip was referred to as the functional reach test score (FRTS) in that direction [36]. Twenty-nine reflective markers were placed on anatomical

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Fig. 2. Schematic of the Trunk Support Trainer (TruST).
landmarks to monitor their upper body movements and estimate the center of mass (COM). Marker attachment positions were selected based on the literature [37]. Nineteen VICON cameras (Fig. 2) surrounding the subjects recorded marker trajectories at 100Hz. The center of pressure (COP) data were collected by a pressure seated mat (Tactilus, NY) at 56 Hz. Subjects were also asked to complete two standard questionnaires: Simulator Sickness Questionnaire (SSQ) [38] and Immersive Tendency Questionnaire (ITQ) [39].

The belt movement trajectory during the PSST was sent to the TruST controller to define the virtual boundary. Sixty-three subjects were randomly assigned to three equal groups: PR group, AR group, and VR group. Reaching targets were categorized into three difficulty levels: basic, medium, and hard. In the PR group, targets were represented as real reflective markers (Fig. 3c), while in the AR and VR groups, they were depicted as virtual bronze, silver, and gold coins (Fig. 3d). For each subject, the basic level targets were placed at his farthest reaching positions in PSST, while the medium and hard level targets were placed at 10% and 20% FRTS farther away from the basic level target, respectively.

During training, subjects were instructed to complete 96 bouts (12 rounds × 8 directions) of reach task with the assistance of TruST. The reaching direction sequence was shuffled across all rounds for all subjects. For each reach, basic, medium, and hard level targets accounted for scores 1, 2, and 3, respectively. Subjects were encouraged to score as high as possible. Fig. 3 e, f, g show the third-person and first-person views of the training session in PR, AR, and VR groups, respectively. Training environments were real in PR and AR groups but virtual in the VR group.

After training, subjects performed the PSST again and filled out four standard questionnaires: SSQ, Witmer & Singer Presence Questionnaire (PQ) [39], Game Engagement Questionnaire (GEQ) [40], and Universal Enjoyment Questionnaire (UEQ) [41].

D. Data Preprocessing

MATLAB (Mathworks, MA) was used for data preprocessing. Data collected from VICON cameras and the pressure seated mat were lowpass filtered using a fourth-order Butterworth filter with cutoff frequencies of 10 and 6 Hz, respectively [42], [43]. For the self-report data collected from questionnaires, a seven-point Likert scale was assigned to each question [39]. We then normalized the total score of each answer sheet to the range 0 ~ 1 by dividing the sum of all question scores by the total possible score.

E. Training Outcome Measures

Training outcome measures are summarized in Fig. 3.

1) FRTS: FRTS assesses the maximum distance a subject can reach while maintaining stability. We used it to evaluate upper limb function and sitting proactive balance for each direction in PSST. This measure has demonstrated high reliability and validity in existing literature [36].

2) Sitting Workspace Area: We extracted the upper-body COM trajectories in PSST and identified the farthest reach points for eight directions to define the sitting stability limits. Connecting these points formed a polygon that represents the sitting workspace. Its area serves as a measure of overall sitting dynamic balance ability [10] and functional independence [9].

3) COP variables: Subjects sat on a pressure mat without foot support during PSST. Reaction forces exerted by the support surface converged at a single point, referred to as the COP. Total excursion and mean velocity are two widely used COP measures to assess how far and how quickly subjects shifted their COM within the base of support during multidirectional reaches [44]. Approximate entropy (ApEn) is a statistical
metric used to quantify the regularity and predictability of time-sequential data [45]. It also serves as a standard COP measure in rehabilitation to assess the complexity of sitting posture control and flexibility in coordinating upper body segments [46]. ApEn values fall within the range of 0 ∼ 2, with higher values indicating greater complexity.

4) HIAR: Active practice amount is critical for measuring training intensity and promoting neural plasticity [17]. To assess this factor, we first extracted the index fingertip trajectory during the baseline PSST. Next, we constructed a polygon that encompasses all trajectory points, representing the baseline reaching workspace. For each subject, we recorded both the total training time and the time spent outside the polygon (i.e., high intense activity time). The high intense activity rate (HIAR) is defined in Equation (1). We used this metric to assess the active practice time in exploring beyond baseline reach limits with the assistance of TruST.

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HIAR = \frac{\text{high intense activity time}}{\text{total training time}} \tag{1}
\]

5) Reach Task Score: Challenging goal-oriented repetitions could foster motor skill exploration in posture training [17]. In this study, the basic, medium, and hard level reaching targets accounted for scores 1, 2, and 3, respectively. For each subject, we calculated the cumulative score for 96 reaches during training to assess motor task performance. The reach task score is another metric to measure the training intensity.

6) SSQ Score: Simulator sickness describes the phenomenon that subjects feel uncomfortable interacting with simulated environments. This discomfort arises when visual cues suggest self-motion, but the vestibular system does not detect the corresponding inertial forces [38]. Simulator sickness usually manifests as nausea, vomiting, eye fatigue, dizziness, ataxia, etc. These symptoms can be exacerbated during XR experiences and RAT with limited training space [32]. In this study, we used SSQ as a self-report symptom checklist to assess the severity of 16 symptoms related to simulator sickness in subjects before and after training.

7) Immersion Score: Immersion level refers to the capacity of an XR system to provide simulated virtual experiences to users. It is an objective metric influenced by both hardware properties (e.g., field of view, rendering frame rate) and software design (e.g., textures, brightness, and interaction design). In this study, we adopted the method proposed by Selzer et al. [47] to calculate immersion scores for our AR and VR systems. These scores were then normalized to the range 0 ∼ 1, representing the relative positions of our AR and VR systems on the RV continuum (PR group defaulted to 0).

8) ITQ Score: Immersive tendency refers to the subjective inclination to become deeply involved in situations and maintain focus on current activities. People with high immersive tendencies may easily ignore external distractions and fully engage in XR experiences, often becoming unaware of their immediate environment and the passage of time [39]. In this study, we used ITQ score to assess the immersive tendency ability of each subject before training. An example question from the ITQ is “Do you ever become so involved in movies, TV dramas, or books that you are not aware of things happening around you?”

9) PQ score: Presence refers to the feeling of being physically present in a virtual environment and perceiving oneself as part of the digital world. It is a subjective metric influenced by psychological state, emotional fluctuation, and XR intervention quality [39]. We used PQ score to assess the presence level during training in the VR and AR groups (PR group defaulted to zero). An example question from the PQ is “How compelling was your sense of moving around inside the virtual environment?”

10) GEQ Score: Engagement refers to the involvement and attention that subjects exhibit when playing a game. It is a subjective metric influenced by mind flow state, psychological absorption, and dissociation [40]. We use the GEQ score to assess the engagement level of each subject during training. An example question from GEQ is “Do you feel that time seems to kind of stand still or stop during training?”

11) UEQ Score: Enjoyment refers to positive experience and satisfaction when playing a game. It is a subjective construct influenced by items such as pleasure, competence, and task challenge level [41]. We used UEQ score to assess the enjoyment level of each subject when performing the training task. An example question from UEQ is: “Do you feel that the activity was pleasurable to you?”

F. Statistical Analysis

We conducted statistical analysis using SPSS (IBM, v29). The significance level was set at 0.05. We employed the Shapiro-Wilk test and visually inspected Q-Q plots to assess data normality.

Mixed between-within group analysis of variance (ANOVA) were performed to assess the impact of different interventions in PR, AR, and AR groups on several variables: FRTS, sitting workspace area, COP variables, and simulator sickness level across two time periods (baseline and post-training). We examined homoscedasticity and multicollinearity using Levene’s and Mauchly’s sphericity tests, respectively. For significant ANOVA results, we performed post-hoc test and used Bonferroni’s inequality procedure for multiple comparisons.

One-way between-groups ANOVA were conducted to compare various measures (HIAR, reach task score, ITQ score, PQ score, GEQ score, and UEQ score) between the three groups. If the ANOVA model indicated significance, we followed up with post-hoc tests using Bonferroni’s inequality procedure.

III. RESULTS

A. Immersion and Presence

Fig. 4 shows the normalized immersion scores for the AR and VR systems developed in this study. AR and VR groups
Fig. 5. Baseline and post-training average FRTSs of PR, AR, and VR groups in eight reaching directions: front (F), front-dominant (FD), dominant (D), back-dominant (BD), and back (B), front-nondominant (FND), nondominant (ND), and back-nondominant (BND). Error bar = 95% CI. Significant pairwise differences between groups are denoted by blue bars and asterisks. * p < 0.05, ** p < 0.01, *** p < 0.001.

Fig. 6. Average sitting workspace areas for three groups in baseline and post-training. Error bar = 95% CI.

B. Functional Reach Performance and Balance

The average FRTS for each group was visually depicted in Fig. 5. After training, all groups exhibited a significant increase of FRTS (p < 0.001) in each direction. Across all directions, the interaction effect between intervention group and test time was statistically significant. As shown in Fig. 5, the increase was significantly greater in the AR and VR groups compared to the PR group. However, there was no significant difference in FRTS improvement between the AR and VR groups, except for the dominant and nondominant sides (Fig. 5 D, ND).

As shown in Fig. 6, all groups exhibited a significant increase in sitting workspace area after training (p < 0.001). The effect sizes (partial η²) were 0.90, 0.96, and 0.96 for the PR, AR, and VR groups, respectively. The increase was more pronounced in the AR and VR groups compared to the PR group, but was not significantly different between the AR and VR groups (p < 0.001 for AR vs. PR and VR vs. PR, p = 1.00 for AR vs. VR).

C. Postural Control

Statistical analysis results of COP variables are summarized in Table I. After training, all groups exhibited a significant increase in COP total excursion during PSST. The increase was more pronounced in the AR and VR groups compared to the PR group, with no significant differences between the AR and VR groups. Only subjects in the PR group shifted their COP faster during PSST after training. The AR and VR groups showed no significant change in the mean COP velocity after training.

ApEn values revealed that all groups experienced significant improvements in postural control complexity and flexibility in coordinating body segments after training. The improvement was greater in the AR and VR groups compared to the PR group. There was no significant difference between the AR and VR groups.

D. Training Intensity

As shown in Fig. 7, subjects in the AR and VR groups underwent more intense training compared to the PR group. Both the HIAR and the reach task scores were significantly
Engagement and Enjoyment

As shown in Fig. 8, subjects in the AR and VR groups exhibited higher level of engagement and enjoyment when performing the training task, in contrast to the PR group. Both the GEQ score and the UEQ score were significantly higher in the AR and VR groups than in the PR group (p < 0.001 for AR vs. PR and VR vs. PR). No significant differences were observed between the AR and VR groups in terms of either the GEQ or UEQ scores.

IV. Discussion

A. (RAT + XR) vs. RAT

Our results indicate that TruST-assisted training significantly improved sitting stability and functional reach performance in all subjects, consistent with our previous research [9], [48]. Additionally, we found that introducing XR into TruST intervention further enhanced its training effectiveness.

Functional reach movements require complex neuromuscular control to achieve motor planning goals while maintaining posture equilibrium [49]. Previous research suggests that the XR interaction may induce various neurophysiological adaptations, such as improved interhemispheric balance, enhanced cortical connectivity, and increased muscle cortical representation [19]. Consequently, XR has the potential to stimulate neural plasticity, which positively impacts motor function. Key factors for promoting neural plasticity include adequate intervention time and repetitive goal-oriented practice [17]. In this study, the AR and VR groups performed the same number of reach movements as the PR group during training, but achieved higher HIAR and reach task score. This implies that subjects in the AR and VR groups spent more time beyond their stability limits, actively exploring and honing motor skills. In other words, they leveraged the TruST robotic platform more effectively—more frequent and longer used of the assistive force field during practice—which led to enhanced dynamic postural control strategies with the consequent ability of reaching the location of the most challenging targets. This might explain why the improvements in the FRTS and sitting workspace area are more pronounced in the AR and VR groups compared to the PR group.

Previous studies suggest that the inherent gamification property of XR could enhance cognitive and emotional involvement, thus encouraging voluntary participation and maximizing the intervention effect [17], [20]. Our results align with the literature. Subjects in the AR and VR groups achieved significantly higher scores in GEQ and UEQ, indicating greater engagement and enjoyment during seated postural training. Many subjects in the AR and VR groups reported being so engrossed in earning virtual coins that they momentarily forgot they were undergoing a training task. In contrast, subjects in the PR group perceived the task as monotonous, so they
attempted to complete it quickly. Previous studies have shown that subjects’ adherence to rehabilitation protocols and their active engagement while receiving the intervention importantly influence the treatment benefits \cite{50}, \cite{51}. Thus, the attitude towards training may have played a substantial role in the intervention effect. The psychological difference could explain the longer training session and the better training outcomes observed in the AR and VR groups within this study.

In post-training PSST, we observed that many subjects in the AR and VR groups realigned their upper body segments to resemble a freestyle swimming posture: tilting the head and rotating shoulders to form a straight line with the extended arm. This adjustment increased their posture complexity and flexibility (Table I, ApEn results), allowing them to reach farther while maintaining posture equilibrium. The AR and VR groups explored and adopted this novel strategy early in the training session, refined, and memorized it in the remaining time. Notably, seven PR group subjects also discovered this strategy before the end of the training session. However, they did not maintain the postural adjustments consistently. In the post-test, the PR group tended to shift the upper body COM rapidly (Table I, COP mean velocity results), compromising posture stability for a longer reach distance. Their movement exhibited a spring-like property: extending out and then retracting swiftly. Our observations suggest that XR interaction could accelerate motor learning in RAT. This enhancement enables early exploration of novel postural strategies, allowing sufficient time for posture standardization and stabilization before fatigue and boredom effects disrupt the learning process. To test this hypothesis, further research is granted to investigate the control mechanisms underlying the motor changes found among the groups. We will analyze the fluctuations in joint angles and segment positions along practice rounds to investigate the movement pattern variations in three groups during the training session.

Some studies employ open-source commercial games for XR posture training \cite{3}, \cite{20}. However, excessive recreational and entertainment features within these games could cause cognitive overload and distract subjects from the rehabilitation task \cite{32}. In this study, we adopted suggestions from the literature \cite{17}, \cite{31}, \cite{52} to develop a custom XR application that balanced entertainment with TruST-assisted postural training requirements. Our application involved randomized reach directions and clear functional reach targets with hierarchical difficulty levels. When the subject successfully reached a target, the virtual coin rotated to provide positive feedback. Besides, instead of traditional controllers, we opted for XR devices that allow direct hand interaction with virtual items, which facilitates the transfer of motor skills learned during training to activities of daily living. Our approach can be extended to other studies to develop novel rehabilitation-oriented XR applications. In addition, we will share our application with the research community following the IRB guidelines to promote the application of XR in RAT.

B. RAT with AR or VR: Comparison & Recommendation

Motion sickness refers to the discomfort experienced after certain movements. Simulator sickness, a subtype of motion sickness, occurs in simulated environments due to mismatch between perceived visual motion and actual vestibular motion \cite{38}. Prior study has reported that XR immersion level is positively correlated with simulation sickness \cite{32}. Our findings are consistent with the literature. In this study, the RAT alone did not cause significant motion sickness in subjects (Table I, PR group, SSQ results). However, when combining XR with the TruST intervention, increasing the immersion score from 0.28 to 0.77 (Fig. 4) led to simulator sickness (Table I, AR and VR groups, SSQ results). Low refresh rate has been identified as the primary factor contributing to simulator sickness in XR experiences \cite{53}. Although the maximum refresh rate of our VR headset is 120 frame per second (fps), same as the gold standard \cite{54}, the actual tested refresh rate varied between 80 and 100 fps due to factors such as model size, model complexity, and virtual hand tracking load. Notably, our AR headset is an optical see-through HMD. Transparent lenses allow for a direct view of the real world, while virtual objects are rendered onto the retina using low-power laser beams \cite{55}. This approach effectively bypasses the refresh rate issue and may explain the significantly lower SSQ score compared to the VR group.

Previous VR studies have highlighted that the reduced awareness of reality may pose safety risks and impact training outcomes \cite{32}. Additionally, when combining VR with RAT, the presence of robotic platform or exoskeletons might hinder effective interaction with virtual items in the simulated environment \cite{31}. In our study, although subjects in the VR group did not physically collide with the TruST stationary frame during training, many of them expressed concerns about potential collisions. Conversely, subjects in the AR group, who could perceive the real training environment through transparent lenses, exhibited greater confidence when reaching in the TruST platform. The psychological difference may account for the significantly lower FRTS improvement on the dominant and nondominant sides in the VR group compared to the AR group (Fig. 5 D, ND). Future study on combining XR with RAT should prioritize examining the potential implications of reduced reality perception. Researchers may consider controlling the immersion level or incorporating simulated virtual robot frames into the virtual environment to address this challenge.

We employed the methodology proposed by Selzer et al. \cite{47} to compute the objective immersion scores for our AR and VR systems. Then we normalized the scores to the range $0 \sim 1$ to position our systems on the RV continuum (Fig. 4). Although future studies may not employ the same XR devices and game applications as ours, researchers could still adopt this approach to position their system on the RV continuum. If their device sit close to our systems, our findings in this study could offer valuable insights for developing their XR enhanced RAT platform. Furthermore, our approach of integrating XR with TruST intervention may facilitate seated postural control recovery in patients with neuromotor disorders. However, additional clinical testing is necessary as certain XR side effects identified in this study could potentially worsen in specific patient populations.
V. CONCLUSION

In this study, we conducted a comparative study by integrating VR and AR into the TruST robotic platform for sitting posture training. Our results indicated that both VR and AR significantly enhanced the effectiveness of the postural control intervention delivered by TruST. The XR experience has the potential to enhance engagement and enjoyment during training. Consequently, combining VR or AR with RAT could increase training intensity, leading to improved motor performance and enhanced balance control. Notably, VR may introduce a higher level of simulator sickness compared to AR. Hence, AR may be more suitable than VR when combined with RAT. Overall, our findings help uncover the effects of introducing XR into RAT and provide insights for developing novel XR-enhanced RAT platforms. Future studies should investigate the neuromuscular control mechanisms underlying the XR-introduced motor changes and the clinical potential of XR-enhanced RAT in patients with neuromotor disorders.

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