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Motion Stabilization Training in Virtual Reality to Reduce Head Movement During MRI Scanning

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Abstract:

Head motion during MRI acquisition degrades image quality and increases rescanning rates. A VR-based motion stabilization training system was developed to teach patients voluntary head control prior to scanning. The system integrates real-time inertial tracking and visual biofeedback to encourage micro-movement awareness. A cohort of 72 participants underwent a 10-minute VR stabilization session before MRI. Head movement was recorded using scanner-based motion tracking during T1-weighted sequences. Participants receiving VR training demonstrated a 39.8% reduction in mean head displacement compared with historical controls (0.62 mm vs. 1.03 mm). The proportion of scans requiring repetition decreased from 18.5% to 6.9%. Training adherence exceeded 95%, and user comfort ratings averaged 4.6/5. VR-guided motion stabilization training significantly improves positional control and scan reliability.

1. INTRODUCTION

Head motion during MRI remains a major source of image degradation, non-diagnostic scans, and examination inefficiency. Even subtle head displacements can produce blurring, ringing, or ghosting artifacts, particularly in high-resolution structural imaging, diffusion sequences, and functional protocols, where spatial precision and signal stability are critical [1]. These motion-related artifacts reduce diagnostic reliability, complicate image interpretation, and often require repeated acquisitions, thereby prolonging scan time and increasing patient burden [2]. In routine practice, motion is therefore not only a technical nuisance but also an important operational issue that affects workflow, cost, and overall examination quality. Recent studies have emphasized that effective motion mitigation should be addressed across the imaging workflow, including pre-scan preparation, in-scan monitoring, and post-acquisition correction, rather than relying on a single downstream solution [3]. In addition, recent work using a standalone head-mounted virtual reality simulator has suggested that realistic pre-exposure to the MRI environment may improve patient readiness and procedural tolerance, highlighting the value of immersive preparation as an upstream strategy for motion control [4].

Considerable effort has been devoted to technical solutions for motion mitigation. Prospective motion correction methods attempt to compensate for movement during image acquisition by updating imaging parameters in real time according to tracked head position [5]. Retrospective approaches, in contrast, attempt to reconstruct or restore motion-corrupted images after acquisition [6,7]. These methods can reduce artifact severity under controlled conditions, but their effectiveness is constrained by several practical factors, including tracking precision, temporal update rate, sequence compatibility, and the magnitude and pattern of patient motion [8]. More recently, deep learning–based methods for motion detection and correction have shown promising performance in specific tasks, yet their robustness across scanners, protocols, patient populations, and heterogeneous motion profiles remains uncertain [9]. As a result, technical correction alone does not fully eliminate the need to reduce motion at its source. Accurate motion tracking is central to both correction and monitoring. Optical tracking systems that use external markers can achieve high positional precision, but they increase setup complexity and may be affected by marker displacement relative to the skin surface [10,11]. Markerless tracking methods have been proposed to simplify implementation and reduce preparation burden, yet maintaining submillimeter accuracy under scanner constraints remains challenging, especially when visibility, geometry, or hardware conditions are suboptimal [12].

These limitations indicate that hardware-based tracking, while valuable, may not provide a complete solution for patients who are naturally prone to movement, anxious during scanning, or unable to sustain stable head posture over time. This is particularly relevant in clinical populations for whom even low-amplitude micro-movements can degrade image quality despite technically sophisticated acquisition or correction pipelines. For this reason, behavioral preparation strategies remain highly relevant. By targeting motion before image acquisition begins, such approaches aim to reduce artifact generation rather than merely compensate for it afterward. Mock-scanner training has been shown to improve stillness in pediatric imaging, especially when participants are familiarized with scanner noise, table motion, and body positioning in advance [13,14]. Virtual reality has emerged as a flexible alternative to physical mock scanners because it can simulate the MRI environment without requiring dedicated room-scale infrastructure [15,16]. Several studies have reported good feasibility, patient acceptance, and potential benefits of VR-based MRI preparation for reducing anxiety and improving scan completion [17]. However, the reported effects on objective motion outcomes remain inconsistent, partly because intervention duration, interaction design, patient population, and evaluation criteria vary substantially across studies [18,19]. In many existing systems, the primary emphasis is placed on environment familiarization and emotional reassurance rather than on direct training of movement control. This distinction is important. Passive familiarization may reduce anticipatory stress, but it does not necessarily teach patients how to maintain stable head posture during acquisition. In practice, successful MRI requires not only psychological readiness but also sustained voluntary control of small movements over several minutes. Interactive VR systems that provide real-time feedback on head displacement may therefore offer an additional advantage by supporting motor awareness and self-regulation before the scan begins. Through visual or multimodal biofeedback, patients may learn to recognize subtle movements that would otherwise go unnoticed and to adjust their behavior in response. Preliminary evidence suggests that active feedback in simulated scanning environments may help reduce head displacement, but validation linked to scanner-derived motion measurements remains limited, and the clinical value of brief pre-scan training protocols has not yet been established clearly [20,21]. Another limitation in the current literature is the relative scarcity of studies that connect pre-scan behavioral interventions with objective in-scanner motion metrics. Many reports focus on feasibility, tolerability, satisfaction, or completion rate, which are important but do not fully capture whether an intervention improves scan stability in a

measurable way [22,23]. When motion is evaluated, it is often described using broad categorical assessments rather than fine-grained quantitative indicators of displacement. This makes it difficult to compare findings across studies or to determine whether reported improvements are large enough to influence image quality and repeat-scan burden in routine practice. A brief, scalable intervention that specifically targets micro-movement control and is evaluated against scanner-recorded motion outcomes would therefore address a meaningful gap in the MRI preparation literature.

Against this background, the present study introduces a VR-based motion stabilization system that integrates inertial tracking with visual biofeedback to increase patient awareness of subtle head movements before MRI acquisition. The system is designed as a short pre-scan training protocol that can be implemented without the infrastructure demands of a physical mock scanner, making it potentially suitable for routine clinical use. The objective of this study is to determine whether this targeted VR training can reduce scanner-recorded head displacement during T1-weighted imaging and lower repeat-scan frequency. The significance of this work lies in its focus on motion prevention rather than motion correction alone. By directly training patients to control micro-movements before entering the scanner, this approach may complement existing tracking and correction technologies, improve image stability, reduce avoidable rescans, and provide a practical patient-centered strategy for enhancing MRI efficiency and quality in everyday clinical settings.

2.Materials and Methods

2.1 Sample and Study Setting

Seventy-two adult participants (18–65 years) scheduled for routine brain MRI were included in this study. Participants had no history of neurological disease, vestibular disorders, or contraindications to MRI or VR use. Recruitment was conducted consecutively over a four-month period at a tertiary imaging center. All scans were performed on the same 3.0 T MRI system using identical T1-weighted acquisition parameters. A historical control group of 81 age-matched individuals scanned under the same protocol during the previous year was used for comparison. Ethical approval was obtained from the institutional review board, and written informed consent was provided by all participants.

2.2 Experimental Design and Control Protocol

A prospective intervention design was used. Participants in the training group completed a 10-minute VR-based motion stabilization session immediately before MRI acquisition. The VR

system provided real-time visual feedback linked to head orientation and acceleration, encouraging voluntary control of small movements. The control group consisted of patients who underwent routine MRI without structured motion training. Both groups received the same positioning procedure, including head padding and standard instructions to remain still. The primary outcomes were mean head displacement during T1-weighted imaging and the proportion of scans requiring repetition due to motion artifacts. The study design was based on the assumption that real-time biofeedback improves motor control and reduces involuntary head motion during scanning.

2.3 Measurement Procedures and Quality Control

Head motion during MRI was measured using scanner-based rigid-body realignment parameters derived from image reconstruction. Translational motion along the x, y, and z axes was recorded for each time frame. Mean and maximum displacement values were calculated for each participant. MRI acquisition parameters, including repetition time, echo time, and voxel resolution, were kept constant across all examinations. Technologists followed a standardized head positioning protocol to reduce variation in padding and coil placement. Scanner calibration was checked regularly according to manufacturer guidelines. Image quality was evaluated through visual inspection for ghosting and automated motion thresholds. Scans with technical artifacts unrelated to motion were excluded from analysis.

2.4 Data Processing and Model Formulation

Motion parameters were processed using a predefined analysis pipeline. Framewise displacement (FD) was calculated to summarize head motion over time. FD was defined as

$$FD_t=|\Delta x_t|+|\Delta y_t|+|\Delta z_t|,$$

where Δx_t , Δy_t, and Δz_t represent translational changes between consecutive frames. The average displacement for each participant was calculated as

$$\overline{D}=\frac{1}{T}\sum_{t=1}^{T} F\, D_t,$$

where T is the total number of frames. To examine group differences while adjusting for age, linear regression was applied:

$$D_i=\beta_0+\beta_1 G_i+\beta_2 A_i+\varepsilon_i,$$

Where D_i denotes mean displacement, G_i indicates group assignment, and A_i represents age.

2.5 Statistical Analysis

Continuous variables were reported as mean ± standard deviation. Normality was assessed using the Shapiro–Wilk test. Independent-sample t-tests were applied to compare displacement values between groups when distribution assumptions were met. The proportion of repeat scans was compared using the chi-square test. Effect size was estimated using Cohen's d. Statistical significance was defined as $p < 0.05$. All analyses were performed using standard statistical software to ensure consistent and reproducible results.

3.Results and Discussion

3.1 Head-motion reduction during T1-weighted scanning

After VR stabilization training, mean head displacement during T1-weighted imaging decreased from 1.03 mm in the reference cohort to 0.62 mm in the trained cohort, representing a 39.8% reduction. This change is important because repeated small head shifts can blur anatomical boundaries and lower image contrast, even when no single movement is large. The findings indicate that short, structured preparation with real-time feedback can improve voluntary control of micro-movements before image acquisition. By reducing motion at the source, the intervention shifts many scans away from the range in which artifacts become visible and compromise diagnostic quality [24,25].

3.2 Reduction in repeat scans and operational impact

The repeat-scan rate declined from 18.5% to 6.9%, showing that motion control translated into fewer reacquisitions. In clinical practice, repeat scans are often required when ongoing minor movement reduces clarity below local quality standards. Lowering motion before scanning therefore improves reliability and preserves scanner time. Compared with strategies that rely on post-acquisition correction, behavioral stabilization prevents artifact formation rather than attempting to repair it later. This prevention-based approach may be particularly useful in routine workflows where scan duration and throughput are tightly managed [26,27].

3.3 Feasibility and user acceptance

Training adherence exceeded 95%, and the average comfort rating was 4.6 out of 5, indicating good tolerance and ease of use. Practical feasibility is essential for motion-reduction strategies, as interventions that increase preparation time or require specialized facilities are difficult to

integrate into daily practice. VR-based preparation programs have demonstrated that structured immersive guidance can be delivered effectively before imaging procedures (Fig.1). The current protocol focuses specifically on motor stabilization rather than general familiarization, yet it maintains the simplicity and acceptability shown in prior VR preparation studies [28,29].



Figure 1 Virtual reality interface showing pre-scan training content used to prepare participants before MRI acquisition.

3.4 Comparison with prospective correction and study limitations

Prospective motion correction reduces artifact severity by adjusting acquisition geometry according to tracked head pose and has enabled high-resolution brain imaging under controlled conditions (Fig.2). However, correction performance depends on tracking accuracy and sequence compatibility, and it may not fully prevent image degradation when motion occurs frequently or within acquisition readouts. The VR stabilization approach acts earlier by reducing head movement before scanning begins, which can lessen reliance on correction systems and lower the likelihood of rescans. Several limitations should be considered. The control comparison was historical rather than randomized, which may introduce unmeasured differences in workflow conditions. Motion was evaluated during T1-weighted imaging only, and the persistence of training effects across longer or more motion-sensitive protocols was not assessed. Further studies should include concurrent randomization and multi-sequence evaluation to confirm generalizability [30].

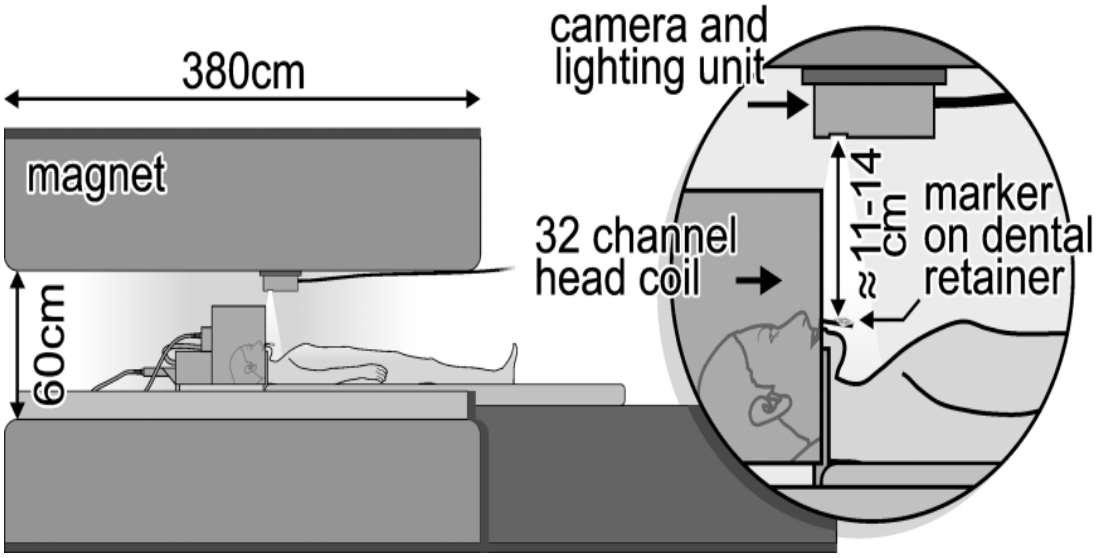


Figure 2 Prospective motion correction system illustrating real-time head tracking and imaging volume adjustment during high-resolution brain MRI.

Conclusion

This study shows that a short virtual reality–based stabilization session can reduce head motion during MRI and decrease the need for repeat scans. Participants who received the training demonstrated lower mean head displacement and improved scan reliability during routine T1-weighted imaging. The findings indicate that voluntary control of small head movements can be improved through brief, feedback-based preparation before scanning. This approach targets motion at its source and can work alongside existing motion tracking and correction techniques. High adherence and favorable comfort ratings suggest that the protocol can be integrated into standard clinical workflows without major changes in infrastructure or scheduling. Several limitations should be noted. The comparison relied on a historical control group, evaluation focused on structural imaging, and long-term retention of the training effect was not examined. Future studies should include concurrent randomization, assessment across multiple MRI sequences, and evaluation in populations with higher motion risk. Despite these limitations, VR-based stabilization training offers a practical method to improve MRI image quality and reduce operational inefficiency related to head motion.

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