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Neurovascular Correlates of Motor Imagery Training in Elite Volleyball Players: A Preliminary fNIRS Study

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Abstract

Background

Motor imagery (MI) training is widely used to support motor learning, but it remains unclear whether mental training of complex sports-specific actions, like the volleyball spike serve, elicits a focal, training-induced hemodynamic activation increase in the primary motor cortex (M1). This preliminary study aimed to investigate the longitudinal effects of a 6 week complex mental training program focused on spike serve imagery on cortical activation in elite professional volleyball players, and to examine the spatial specificity of this adaptation using functional near-infrared spectroscopy (fNIRS).

Methods

Nine elite male professional volleyball players from a single team completed a 6 week, sport-specific MI training program targeting the spike serve within a longitudinal pre-test/post-test design. Cortical hemodynamic responses were recorded during a standardized block-design imagery task using a portable fNIRS system. Regions of interest on the primary motor cortex were anatomically defined based on the motor homunculus as Focal M1 (hand/arm representation), Dorsomedial M1 (dmM1; trunk/shoulder representation), and Ventrolateral M1 (vlM1; orofacial representation). Psychometric changes were assessed using the Sport Imagery Ability Questionnaire (SIAQ).

Results

Following the 6 week training, oxy-hemoglobin levels during the motor imagery condition significantly increased in the target Focal M1 region across both hemispheres (left: $q < 0.0001$; right: $q = 0.021$). This enhanced hemodynamic excitability extended to the adjacent dmM1 region but did not spread to the orofacial vlM1 area ($q > 0.90$), indicating that training-induced plasticity remained strictly specific to task-relevant anatomical representations. Furthermore, the improvement in self reported imagery ease, as indicated by SIAQ difference scores, was strongly and positively correlated ($r = 0.960$, $q = 0.042$) with the task-rest contrast change in the left Focal M1.

Conclusions

Six weeks of MI training enhances anatomically specific hemodynamic excitability in the primary motor cortex. The significant correlation between improved imagery ease and relative hemodynamic changes in the left M1 suggests that mental rehearsal of a complex, whole-body task like the spike serve engages left-lateralized praxis networks. These findings provide novel evidence that mental training induces highly focal cortical adaptations in elite athletes, extending the principle of somatotopically localized neuroplasticity to complex sports skills.

Trial Registration

Clinical trial number: not applicable.

1. Background

Motor imagery (MI) refers to the mental simulation of a motor action without its overt physical execution and is widely used as a cognitive strategy to support motor learning and performance. Neuroimaging evidence indicates that MI recruits a distributed neural network involving sensorimotor and premotor regions, including the supplementary motor area (SMA), premotor cortex (PMC), and parietal areas, with partial overlap between the neural substrates underlying imagined and executed actions (1). Importantly, this overlap should not be interpreted as complete neural equivalence, as MI also places substantial demands on frontal and parietal associative networks involved in higher-order cognitive processing (1, 2). In athletic populations, these neural responses appear to be further shaped by accumulated motor expertise; a recent activation likelihood estimation meta-analysis demonstrated greater recruitment of the precentral and middle frontal gyri during MI in athletes than in non-athletes, supporting an experience-dependent organization of imagery-related neural activity (3). Collectively, these findings suggest that the neural organization of MI reflects not only the internal simulation of movement but also the performer's accumulated motor experience, providing a rationale for examining MI-related cortical responses within complex, sport-specific actions.

The cortical response associated with MI appears to be shaped by the interaction between motor expertise and task complexity rather than by expertise alone. Recent functional near-infrared spectroscopy (fNIRS) evidence demonstrated that expert athletes exhibited lower cortical recruitment than novices when imagining relatively simple sport-specific actions, whereas imagery of complex actions elicited greater cortical activation in experts, suggesting that experienced performers dynamically scale neural recruitment according to task demands (4). Consistent with this perspective, fNIRS research involving whole-body sport-specific imagery has shown that hemodynamic responses during MI vary according to skill level and task difficulty, further supporting the role of expertise and movement demands in shaping imagery-related cortical activity (5). This interaction may be particularly relevant to the volleyball spike serve, a complex motor skill requiring the coordinated integration of whole-body and upper-limb actions. Specifically, effective execution requires precise control of the magnitude and timing of angular momentum across body segments, including the forearm and hand, to facilitate rapid arm-swing execution during the aerial phase (6). For elite volleyball players, imagery of such a highly practiced yet biomechanically complex action therefore provides an ecologically relevant model for examining how expertise-dependent motor representations are expressed at the cortical level. However, despite the widespread use of MI in sport, the neurovascular responses associated with imagery of complex volleyball-specific actions, particularly in highly trained athletes, remain poorly characterized.

Beyond the task-specific characteristics of MI, an important question concerns how repeated imagery practice modifies the spatial organization of cortical hemodynamic responses over time. Longitudinal MI studies suggest that repeated practice may alter the recruitment of motor-related networks, including the SMA, PMC, and parietal regions (7–9). Yet, in neuroimaging techniques like fNIRS, distinguishing whether cortical responses represent a "broad network activation" or a "spatially specific focal activation" depends on the anatomical precision of optode placement. Many fNIRS studies in sports science fail to isolate specific subregions on the cortical homunculus (e.g., only the hand/arm representation area) because they define broad regions of interest (ROI) based on the theoretical 10–20 system. The literature explicitly emphasizes that specifically localizing the "hand knob" area directly over the primary motor cortex (M1) increases signal sensitivity, particularly in tasks involving throwing and striking skills (10–12). Without such fine, anatomically targeted localization, the blending of signals with adjacent cortical areas is inevitable, making it unclear which region truly exhibits a focal increase in response to training (13, 14).

It is well established that long-term mental training paradigms based on MI induce activation across broad sensorimotor networks; however, it remains unclear in the fNIRS literature whether a focal, training-induced increase in activation can be achieved in a strictly isolated primary motor area, and whether this response extends to adjacent regions. In this context, the aim of this pilot study is to examine the effects of 6 weeks of complex mental training (spike serve imagery) on cortical activation in professional volleyball players using a longitudinal fNIRS design. The primary hypothesis of the study is that six weeks of training will significantly increase oxyhemoglobin (HbO) levels during motor imagery in the primary target region (Focal M1; hand/arm representation area), which was defined using a priori anatomical references. The secondary aim of the study is to test the spatial specificity of this focal adaptation. Accordingly, it was hypothesized that the training-induced excitability would remain anatomically constrained and would not spread to functionally distinct areas.

2. Methods

2.1. Participants

Fourteen elite male professional volleyball players who train regularly were included in this study. Shortly after the data collection was completed, the participants' team won first place in the International School Sport Federation School Volleyball Championship, demonstrating the high expertise level of the sample. Of the initial cohort, three participants did not complete both sessions and were thus ineligible for paired analyses. Following fNIRS data quality checks and signal-to-noise ratio evaluations of the remaining eleven participants, the data of two additional participants were excluded from the analysis. Ultimately, all statistical analyses were conducted on a final paired analytic sample of 9 participants (mean age = 17.2 ± 0.7 years, height = 193.3 ± 4.2 cm, weight = 84.2 ± 7.7 kg, body mass index = 22.5 ± 1.6 kg/m²) who had technically valid recordings for both the pre-test and post-test. A detailed flowchart illustrating the participant inclusion process and specific exclusion criteria is presented in Fig. 1. The study protocol

was approved by the Gazi University Ethics Committee (Approval ID: 2026 – 1585), and written informed consent was obtained from all participants.

2.2. Study Design

The study employed a single-group longitudinal pre-test/post-test design to examine changes in cortical hemodynamic responses following motor imagery (MI) training for the volleyball spike serve. All participants were student-athletes residing at the same boarding school and followed a common daily schedule throughout the study period. Accordingly, they shared the same residential and training environment, with broadly standardized school, meal, sleep–wake, and volleyball training schedules. This residential setting helped minimize between-participant variability associated with differences in daily routines and environmental conditions.

2.3. Motor Imagery Training Protocol

The MI training program was conducted over six weeks, three days per week, with two sessions performed on each training day: the first immediately after the scheduled volleyball training session and the second before bedtime. The intervention protocol was developed by an expert sport psychologist and adapted from Suinn's Visual Motor Behavior Rehearsal approach (15). The training sessions were delivered through audio recordings narrated by the athletes' team coach, whose voice and verbal instructions were familiar to the participants from their regular volleyball training, and consisted of three sequential phases. The first phase involved relaxation exercises designed to reduce physical and mental tension and facilitate readiness for imagery practice. The second phase consisted of multimodal imagery practice incorporating visual, auditory, and kinesthetic components. In the third phase, participants engaged in sport-specific behavioral rehearsal by mentally simulating the volleyball spike serve within scenarios designed to approximate competitive performance conditions. Thus, the protocol progressed systematically from relaxation to multisensory imagery and subsequently to the mental rehearsal of the target sport skill under competition-relevant conditions.

2.4. fNIRS Experimental Paradigm

The recording sessions were based on a standardized block design paradigm while participants sat in a resting state. The session began with a 180-second pre-rest (B) block to acquire the hemodynamic baseline. To maximize the ecological validity of the study, the auditory instructions provided during the experiment were generated directly from voice recordings of the team's own coach. In this context, a 60-second sensory warmup (S) block, guided by the coach's voice, was presented to standardize specific motor and sensory arousal.

During the main experimental phase, Motor Imagery blocks (M) lasting 25 seconds each and 25-second Imagery Rest blocks (R) were presented consecutively in an alternating sequence for 10 repetitions. During the motor imagery blocks, participants were asked to mentally rehearse their own spike serve routines in synchronization with the coach's commands. The recording concluded with a 180-second post-rest (P) period.

2.5. Sport Imagery Ability Questionnaire (SIAQ)

Sport imagery ability was assessed using the Sport Imagery Ability Questionnaire (SIAQ), developed by Williams and Cumming (16). The SIAQ is a 15-item self-report instrument comprising five subscales that assess skill, strategy, goal, affect, and mastery imagery ability. Each item is rated on a 7-point Likert-type scale ranging from 1 (very hard to image) to 7 (very easy to image), with higher scores indicating greater perceived imagery ability. The original validation study supported the five-factor structure of the SIAQ and demonstrated satisfactory internal reliability across its subscales (16). In the present study, the SIAQ was administered under the supervision of the research team immediately before the pre- and post-intervention fNIRS recording sessions to assess changes in self-reported sport imagery ability across the six-week MI training period.

2.6. Data Acquisition and Anatomical ROI Localization

Cortical hemodynamic responses were acquired using a portable continuous-wave fNIRS system (Artinis Brite24) equipped with 24 standard long-separation optical channels, recording at wavelengths of 760 and 850 nm with a nominal sampling rate of 50 Hz. The channel layout was configured based on anatomical reference points over an optode grid aligned according to the standard 10–20 electroencephalography system, and the topographic projections of the optodes on the target cortical areas were verified by the expert anatomist on the research team. Accordingly, the C3 and C4 points, corresponding to the left and right motor cortices, were set as the respective source (Tx8 and Tx2) references, while detectors D4 and D5 were positioned on the midline (Cz).

To test the study's spatial specificity hypothesis, a priori Regions of Interest were defined based on the physical distances of the channels to the midline (Cz). Referencing robust anatomical literature indicating that the cortical representation area for the hand and arm (hand knob) on the motor homunculus is localized immediately medial to the C3/C4 points (17), the channels in the 7.5 cm band were designated as the primary ROI, the Focal M1 region. To control for the spatial specificity of the training effects, two separate exploratory adjacent regions were defined: channels closer to the midline (1.5 and 4.5 cm bands) were classified as Dorsomedial M1 (dmM1), and channels moving inferiorly away from the hand representation (10.5 and 12 cm bands) were classified as Ventrolateral M1 (vlM1). The schematic representation of the fNIRS optode montage and the spatial configuration of these defined ROIs are presented in Fig. 2.

2.7. fNIRS Data Preprocessing

The preprocessing steps of the raw fNIRS data were performed using the Brainstorm (MATLAB) software and the NIRSTORM plugin. For the detection of bad channels that degrade signal quality, the Scalp Coupling Index threshold was set to 75 and the power threshold to 10; channels reaching saturation were automatically rejected. It has been shown in the literature that high hair density in the motor and vertex regions systematically leads to a high bad channel ratio in fNIRS measurements; this was also confirmed by the data characteristics of our study (18). Motion-related artifacts in valid

channels were corrected using the Temporal Derivative Distribution Repair method. A 3rd-order infinite impulse response band-pass filter between 0.01 and 0.2 Hz was applied to the data to filter out physiological noise (heartbeat, respiration) and slow systemic drifts. Optical density data were converted into relative oxy-hemoglobin (HbO) concentration changes using the Modified Beer-Lambert Law. For this conversion, the age parameter was set to 20, and the reference baseline was obtained directly from the pre-rest (B) block.

2.8. Statistical Analysis

Condition-based hemodynamic response amplitudes (beta coefficients) were estimated separately for each participant and channel using the first-level general linear model (GLM) module of NIRSTORM (canonical hemodynamic response function). The pre-coloring method was utilized to correct for temporal autocorrelation in the noise. The Imagery Rest (R) blocks were excluded from the design matrix to maintain the reliability of the GLM estimates and prevent methodological collinearity risks arising from the high degree of overlap (mirror-image effect) with the consecutive M blocks. To visualize the temporal dynamics of the cortical activation, model-implied hemodynamic response function (HRF) time courses were reconstructed for each participant by scaling the canonical double-gamma HRF with the condition-specific amplitude and baseline beta estimates derived from the first-level GLM.

In the second-level group statistics, Linear Mixed-Effects (LME) models were employed to effectively accommodate the unbalanced data structure caused by bad channel removal and to ensure that all valid participant data were retained in the analyses. For the pre-post analyses testing the primary hypothesis, an LME model was constructed specifying Session as the fixed effect and Subject and Channel as random intercepts (HbO ~ Session + (1|Subject) + (1|Channel)). Similarly, for within-session condition differences, Condition was entered as the fixed effect (HbO ~ Condition + (1|Subject) + (1|Channel)). To further test the spatial specificity hypothesis, cross-ROI comparisons were conducted separately within each session (Pre-test, Post-test) and condition (M, B). For each hemisphere, a separate LME model was constructed with ROI (Focal M1, dmM1, vlM1) as the fixed effect (HbO ~ ROI + (1|Subject) + (1|Channel)), and the estimated marginal means for all three pairwise ROI comparisons (Focal M1–dmM1, Focal M1–vlM1, dmM1–vlM1) were extracted. All primary LME estimations were performed using the Maximum Likelihood (ML) method. To ensure maximum statistical robustness against the potential inflation of Type I error rates associated with standard ML estimation in complex longitudinal designs (19, 20), an additional sensitivity analysis was conducted. Accordingly, the primary findings were re-estimated across all region and hemisphere combinations using Restricted Maximum Likelihood (REML) estimation paired with the Satterthwaite approximation for degrees of freedom, and the results from both approaches were compared for statistical consistency.

Finally, the False Discovery Rate (FDR) correction was applied to control for Type I errors arising from multiple comparisons. Test groups reflecting different hypothesis types (Focal M1 Pre-Post, dmM1/vlM1 Pre-Post, and Within-Session comparisons) were evaluated as separate families to calculate q-values. The level of statistical significance was set at $q < 0.05$ following the FDR correction.

Pre- and post-test differences in the Sport Imagery Ability Questionnaire total scores were analyzed using a paired-samples t-test and cross-validated with the non-parametric Wilcoxon signed-rank test to ensure robustness against normality assumptions. Effect sizes were reported using Cohen's d. Pearson and Spearman correlation coefficients were used to examine the relationship between psychometric improvement, measured by SIAQ difference scores, and specific neural changes, namely the Post-Pre HbO changes for both the absolute M condition and the M-B contrast in the Focal M1. Given the small sample size, the FDR correction was applied across the entire fNIRS-SIAQ correlation matrix to rigidly control for Type I error. Descriptive statistics are presented as mean ± standard deviation (SD).

3. Results

3.1. Effect of the Six Week Motor Imagery Training

When examining the hemodynamic data acquired before (pre-test) and after (post-test) the six-week training, a significant increase in favor of the post-test (Post > Pre) was detected in the oxy-hemoglobin levels during the Motor Imagery (M) condition in the Focal M1 region (left Focal M1: $\beta = 8.64$ μM, $t(35) = 6.91$, $q < 0.0001$; right Focal M1: $\beta = 6.83$ μM, $t(40) = 2.62$, $q = 0.0208$) (Fig. 3).

Analysis of the pre-post changes in the adjacent regions revealed no significant difference in the left hemisphere of the Dorsomedial M1 (dmM1) region ($t(68) = -0.19$, $q = 0.9487$), whereas a significant increase in favor of the post-test (Post > Pre, $\beta = 5.72$ μM, $t(53) = 3.94$, $q = 0.0008$) was found in the right hemisphere. In the Ventrolateral M1 (vlM1) region, no statistically significant difference was observed between the pre-test and post-test for the M condition (left vlM1: $t(45) = -0.45$, $q = 0.9013$; right vlM1: $t(47) = -0.42$, $q = 0.9013$) (Fig. 3).

Beyond the overall increase in activation, the temporal profile of the hemodynamic response reveals a distinct training effect. The reconstructed time courses (Fig. 4) demonstrate that cortical perfusion during the post-test session reaches a higher peak and maintains a more sustained HbO amplitude throughout the entire task duration.

Examining the M-B contrast, which reflects the difference between the task and rest conditions, significantly higher values (Post > Pre) were found in the post-test compared to the pre-test in the Focal M1 region (left: $\beta = 31.66$ μM, $t(35) = 6.49$, $q < 0.0001$; right: $\beta = 22.62$ μM, $t(40) = 4.64$, $q < 0.0001$) and the dmM1 region (left: $\beta = 13.95$ μM, $t(68) = 4.15$, $q = 0.0005$; right: $\beta = 19.22$ μM, $t(53) = 7.86$, $q < 0.0001$). In contrast, no significant pre-post difference was detected for the M-B contrast in the vlM1 region (left: $q = 0.9863$; right: $q = 0.5664$).

Furthermore, analyzing the longitudinal change within the Pre-rest (B) condition itself revealed that the baseline values in the post-test session were significantly lower than in the pre-test session (Pre > Post) in the Focal M1 (left: $\beta = -22.88$ μM, $t(35) = -5.07$, $q < 0.0001$; right: $\beta = -15.58$ μM, $t(40) = -4.56$, $q < 0.0001$) and dmM1 regions (left: $\beta = -14.55$ μM, $t(68) = -5.63$, $q < 0.0001$; right: $\beta = -13.44$ μM, $t(53) = -$

5.35, q < 0.0001). This difference was not statistically significant in the vlM1 region (left: q = 0.9487; right: q = 0.6312).

3.2. Within-Session Condition Comparisons

The pre-test and post-test sessions were examined internally through pairwise comparisons across conditions. In the pre-test session, no statistically significant difference was detected between the M and B conditions in the Focal M1 region (left: t(32) = 0.40, q = 0.7539; right: t(36) = 0.21, q = 0.8556). However, in the post-test session, hemodynamic values for the M condition were found to be significantly higher than the B condition (M > B) in the same region (left: t(38) = − 5.67, q < 0.0001; right: t(44) = − 5.30, q < 0.0001). This significant M > B difference was also replicated in the dmM1 region (left: t(80) = − 5.37, q < 0.0001; right: t(62) = − 4.15, q = 0.0004). Furthermore, analyses revealed that none of the within-condition comparisons (including M vs. B and S vs. B) in the vlM1 region during the post-test session reached statistical significance (q > 0.05).

3.3. Spatial Differentiation Across ROIs

To directly test whether the activation peaks in the defined ROIs were spatially distinguishable from one another, pairwise cross-ROI comparisons were conducted within each session. During the M condition, no robust differences were found among the three ROIs at pre-test in either hemisphere (all q > 0.05, except for a marginal difference in the left hemisphere). However, at post-test, the target Focal M1 exhibited significantly higher HbO levels compared to both the adjacent dmM1 (left: t(59) = − 4.07, q < 0.001; right: t(53) = − 3.75, q = 0.0018) and the control vlM1 (left: t(42) = − 4.32, q < 0.001; right: t(48) = − 3.36, q = 0.0046). The dmM1 and vlM1 regions did not significantly differ from each other (all q > 0.35). This clearly indicates that Focal M1 emerged as a spatially distinct, highly localized activation peak specifically as a result of the six-week training.

Analysis of the Pre-rest (B) condition further corroborated the regional specificity of the baseline drift. While no significant cross-ROI differences were observed at pre-test (all q > 0.18), the post-test session revealed a significant spatial dissociation in the right hemisphere. Specifically, the control vlM1 region exhibited significantly higher baseline values than both Focal M1 (t(48) = 3.13, q = 0.018) and dmM1 (t(57) = 3.42, q = 0.014). This pattern perfectly aligns with our longitudinal findings, confirming that the physiological baseline reduction selectively occurred in the task-relevant primary and adjacent motor networks, sparing the orofacial control region.

3.4. LME Model Validation

To confirm that the statistical decisions in the primary ML-based LME analyses were not driven by an inflation of Type I error due to the small sample size, an additional sensitivity analysis was performed using the REML+Satterthwaite method. When comparing the two methods, no discrepancies in statistical significance (α = 0.05) were observed across any region, hemisphere, or condition combination. The model estimates, standard errors (SE), and p-values differed only negligibly between

the two approaches. This demonstrates that the reported fNIRS hemodynamic findings are mathematically robust and reliable.

3.5. Changes in Imagery Ability and Their Correlation with Cortical Hemodynamic Responses

When evaluating the psychometric impact of the six-week motor imagery training, the post-test SIAQ total scores of the entire cohort (n = 14; 78.07 ± 19.04) were found to be significantly higher than their pre-test scores (68.71 ± 20.81) ($t(13) = 2.61$, $p = 0.021$, Cohen's $d = 0.698$). The non-parametric Wilcoxon signed-rank test confirmed this increase independently of normality assumptions ($p = 0.020$). This significant improvement in imagery capacity was also observed within the elite sub-sample included in the fNIRS analysis (n = 9) ($t(8) = 2.86$, $p = 0.021$).

Investigating the relationship between fNIRS hemodynamic change metrics in the Focal M1 region and the SIAQ difference scores revealed a statistically significant positive correlation between the M-B (Task-Rest) contrast change in the left Focal M1 and the SIAQ difference score following FDR correction ($r = 0.960$, $p = 0.002$, $q = 0.042$, n = 6). In contrast, no significant relationship was found between the change in the absolute M condition itself (ΔM) and the SIAQ difference score in either hemisphere (left: $r = 0.112$, $q = 0.988$; right: $r = -0.084$, $q = 0.988$). Furthermore, when this correlation analysis was expanded to the adjacent dmM1 and vlM1 regions, no statistically significant correlations were detected between any fNIRS metric (M or M-B) and the SIAQ difference scores following FDR correction (all $q > 0.05$).

4. Discussion

The primary objective of this study was to investigate the longitudinal effects of a six-week motor imagery training on cortical hemodynamics and to map the spatial specificity of this process using fNIRS. Our findings demonstrated that oxy-hemoglobin (HbO) levels during motor imagery (M) significantly increased in the primary target region, Focal M1, across both hemispheres following the training. Crucially, while this enhanced hemodynamic excitability extended to the adjacent dorsomedial region (dmM1) associated with the upper extremity and trunk representations, it did not spread to the ventrolateral orofacial motor control area (vlM1). As schematically illustrated by the motor homunculus mapping in Fig. 5, this lack of activation in the vlM1 confirms that the training-induced plasticity remained strictly specific to the task-relevant anatomical representations, rather than causing a generalized global cortical spread. Finally, at the subjective level, the improvement in imagery ease (SIAQ difference scores) was found to be directly and strongly correlated ($r = 0.960$) with the target-specific activation difference in the left motor cortex.

The significant increase in HbO observed in the Focal M1 region following six weeks of motor imagery training in our study strongly aligns with existing neuroimaging literature, which suggests that mental practice enhances cortical excitability. Longitudinal studies indicate that repetitive imagery training upregulates hemodynamic responses in motor areas, specifically M1 (5, 21). Notably, Wu et al. emphasize that motor imagery elicits task-related HbO changes in the motor cortex that parallel those of

actual motor execution (21). In our study, the neuroplastic adaptation observed in the target cortical network as a result of imagining a complex whole-body movement like the volleyball spike serve corroborates previous fNIRS findings reporting skill-level-dependent increases in cortical activation among athletes. This post-test increase is thought to reflect neuroplastic reorganization triggered by long-term imagery practice rather than a transient physiological fluctuation. Multimodal (fNIRS-fMRI) imaging studies further confirm that sustained mental training enhances hemodynamic responses in M1 and premotor areas, leading to lasting efficiency in motor planning networks (22, 23). Therefore, the significant post-training enhancement in cortical activation is the focal hemodynamic reflection of neural networks developing and strengthening within the target motor cortex as a direct result of mental practice.

A key finding of our study is that the training-induced hemodynamic enhancement remained anatomically localized and did not spread to the orofacial motor control area (vlM1). A major confounding factor in fNIRS research is the potential for observed HbO increases to stem from diffuse systemic physiological noise, such as autonomic arousal, rather than true neural activation (21). While foundational multimodal (fNIRS-fMRI) studies have established that basic upper-limb motor imagery elicits somatotopically aligned signals in canonical M1 regions (23), our study extends this principle to a longitudinal paradigm involving a complex athletic skill. Specifically, the imagery of the upper-limb-dominant spike serve elicited significant excitability in the Focal M1 without causing significant changes in the adjacent vlM1 region, which clearly reflects this somatotopic differentiation. Moreover, our cross-ROI analyses definitively proved that Focal M1 emerged as a distinct, spatially isolated activation peak at post-test, significantly outperforming both adjacent and control regions. Although motor imagery can recruit a broader network in adjacent areas such as the dmM1 (5, 22), this specific adjacent recruitment is highly consistent with the biomechanical requirements of the spike serve. Executing a forceful, asymmetric upper-limb strike in mid-air necessitates intense contralateral postural stabilization and core activation; thus, the concurrent hemodynamic enhancement in the dmM1 reflects the mental rehearsal of these essential compensatory whole-body mechanics. Conversely, the strict absence of signal spread to the facial representation (vlM1) serves as a robust internal control. This localized response strongly suggests that the observed excitability is not a byproduct of systemic noise, but rather a highly task-specific, neurogenic cortical adaptation adhering to somatotopic organization.

In longitudinal fNIRS designs, multi-session studies emphasize the critical importance of meticulously separating true task-related neuroplasticity signals from nonspecific baseline drifts (23, 24). Our analyses revealed that Pre-rest (B) HbO levels in the post-test session significantly decreased compared to the pre-test session within the target motor regions (Focal M1 and dmM1). In the literature, such baseline reductions across repeated imaging sessions are often attributed to participant familiarization with the laboratory environment (habituation), autonomic relaxation, or long-term vascular adaptations (25, 26). Importantly, our findings analytically demonstrated that the amplified magnitude of the M-B contrast in the post-test session is driven by a dual mechanism: the significant absolute increase in HbO during the imagery condition itself (Post-test M > Pre-test M) reflects true hemodynamic strengthening (neuroplasticity), while the concurrent decrease in the baseline condition (Post-test B < Pre-test B)

contributes to the contrast through physiological habituation. Furthermore, this baseline drift was observed exclusively in the task-relevant motor regions (Focal M1 and dmM1) and was absent in the orofacial vlM1 area. This spatial specificity suggests that the observed baseline drift is not merely a global physiological artifact, but rather a focal adaptation. Specifically, this localized baseline reduction reflects enhanced neural efficiency within the target motor networks, allowing the system to transition more effectively between resting and active states after six weeks of training.

Another notable outcome of our study is that the improvement in imagery ease (SIAQ scores) recorded at the psychometric level was directly linked to the relative hemodynamic changes (M-B contrast) at the neural level. Our analyses revealed a strong positive correlation ($r = 0.960$, $p = 0.002$, $q = 0.042$) between the subjects' SIAQ difference scores and the M-B contrast change (Post-Pre) in the left Focal M1. This neuro-cognitive concordance demonstrated clear spatial specificity, as no such correlations were observed in the adjacent dmM1 and vlM1 regions. This suggests that the self-reported cognitive adaptation is localized to the primary target motor representation rather than reflecting a global cortical epiphenomenon. While multimodal neuroimaging studies report that individuals with high imagery ability exhibit stronger focal HbO and total hemoglobin increases in target areas (23), our findings indicate that this relationship is driven by the widening of the dynamic range shaped by the baseline drop (B) rather than an absolute increase in task activation (M) alone. In other words, the ability to perform mental practice more clearly and effortlessly aligns with the motor cortex's ability to transition more efficiently between resting and task states, rather than merely amplifying its absolute firing intensity. The observation that this correlation was lateralized to the left hemisphere is consistent with motor lateralization and praxis processes. The literature emphasizes that the left hemisphere plays a dominant role in the lateralization of complex motor planning, multi-step actions (praxis), and motor tasks requiring whole-body coordination (27). The imagery of a complex athletic action like the volleyball spike serve, which demands a high degree of postural control, sequential timing, and asymmetrical body planning, may have specifically engaged the praxis networks of the left hemisphere. Therefore, this significant neuro-cognitive concordance in the left motor cortex suggests that mental practice is not merely an abstract cognitive effort, but a concrete neurophysiological adaptation mediated by left-lateralized praxis mechanisms, encompassing enhanced task-rest efficiency. From a broader sports science perspective, this enhanced neural efficiency achieved through structured mental training may act as a neurophysiological buffer, helping elite athletes optimize cognitive load and maintain psychological resilience during high-stakes competitions.

Several methodological limitations should be considered when interpreting the findings of this study. First, the sample size is relatively small ($n = 9$), and the study lacks an independent control group. However, the inclusion of international-level elite volleyball players significantly ensured the quality and homogeneity of the data, and statistical power was maximized by employing linear mixed-effects models within a longitudinal, within-subject design. Second, short-separation channels were not utilized to directly filter scalp-derived extracortical physiological noise in the fNIRS measurements. Nevertheless, the inclusion of the orofacial vlM1 region as an internal anatomical control, which exhibited no

significant activation spread, strongly supports that the observed hemodynamic enhancement reflects true task-related focal cortical activation rather than systemic noise.

5. Conclusion

In conclusion, this study demonstrates that six weeks of motor imagery training enhances anatomically specific hemodynamic excitability in the primary motor cortex. Furthermore, the significant correlation between improvements in self-reported imagery ease and relative hemodynamic changes in the left M1 suggests that imagining a complex, whole-body task like the spike serve engages left-lateralized praxis networks. Although based on a relatively small cohort of elite athletes, these findings indicate that mental training induces highly focal cortical adaptations. Future research with larger samples is warranted to explore how these neural mechanisms directly translate into actual on-field sports performance and the overall psychological well-being of elite athletes.

Abbreviations

dmM1: Dorsomedial primary motor cortex; FDR: False discovery rate; fNIRS: Functional near-infrared spectroscopy; GLM: General linear model; HbO: Oxyhemoglobin; HRF: Hemodynamic response function; LME: Linear mixed-effects; M1: Primary motor cortex; MI: Motor imagery; ML: Maximum likelihood; PMC: Premotor cortex; REML: Restricted maximum likelihood; ROI: Region of interest; SD: Standard deviation; SE: Standard error; SIAQ: Sport Imagery Ability Questionnaire; SMA: Supplementary motor area; vlM1: Ventrolateral primary motor cortex

Declarations

Ethics approval and consent to participate

The study protocol was approved by the Gazi University Ethics Committee (Approval ID: 2026-1585). The study was conducted in accordance with the Declaration of Helsinki. Written informed consent was obtained from all participants, and written informed consent was additionally obtained from the parents or legal guardians of all participants under 18 years of age.

Consent for publication

Not applicable.

Availability of data and materials

The datasets generated and/or analyzed during the current study are not publicly available due to the sensitive nature of the identifiable neuroimaging and personal data collected from participating athletes, and the terms of the informed consent obtained, but are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

All authors contributed to the conception and design of the study. MSI and IG performed the fNIRS recordings and conducted the data preprocessing and statistical analyses. OO and IY coordinated participant recruitment and administered the motor imagery training program. EC and SCP collected the psychometric data and contributed to data curation and interpretation. MSI and HB verified the anatomical localization of the optode montage. HB supervised all stages of the study. All authors contributed to drafting the manuscript and read and approved the final version.

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Trial Registration

Clinical trial number: not applicable.

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Figures

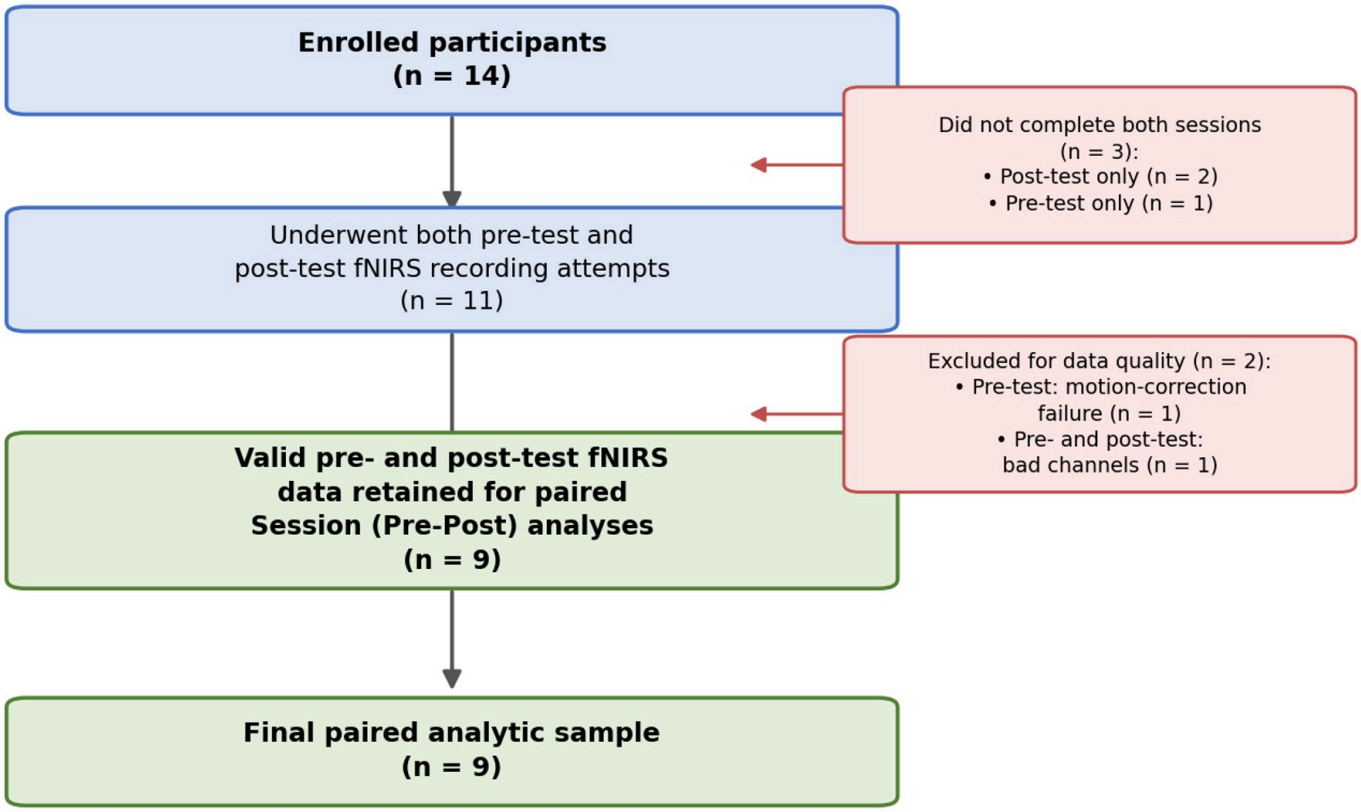


Figure 1

Participant flow diagram. Fourteen participants were enrolled in the study, of whom eleven completed both pre-test and post-test fNIRS recording attempts; the remaining three completed only one session (post-test only, n=2; pre-test only, n=1) and were not eligible for paired analyses. Of the eleven participants with both sessions attempted, two were excluded due to data quality issues (one for motion-correction failure at pre-test; one for bad channels affecting both pre- and post-test recordings), yielding a final paired analytic sample of nine participants for all Session (Pre-Post) fNIRS analyses.

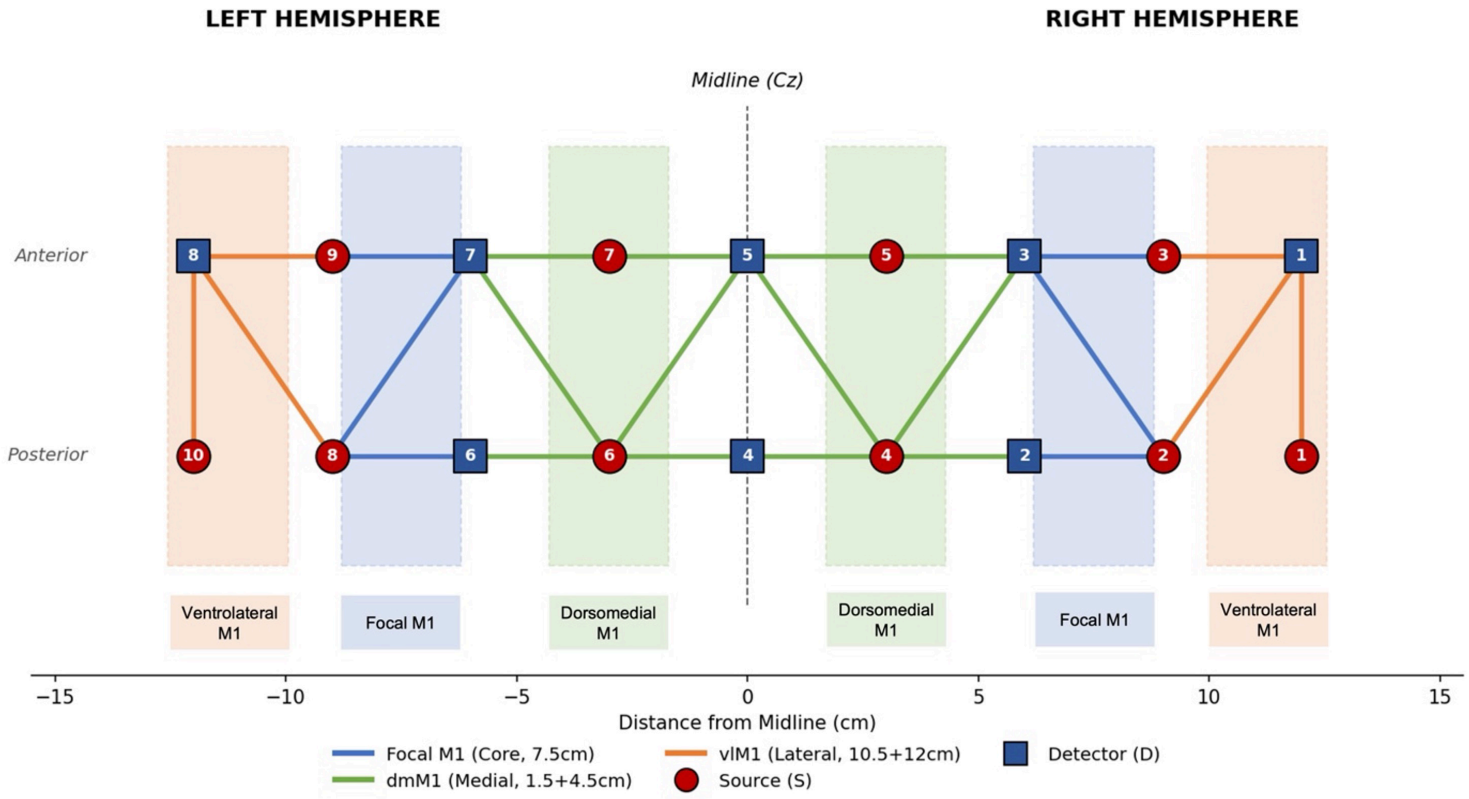


Figure 2

fNIRS optode montage and region of interest (ROI) definitions. Red circles represent sources (S1–S10), and blue squares represent detectors (D1–D8); the montage is based on the physical optode grid on the cap (9 columns × 2 rows [Anterior/Posterior], 3 cm inter-column distance). The midline (Cz) is indicated by the dashed vertical line, and the C3 and C4 anchor points are labeled below their respective columns. Each colored line represents a channel (source-detector pair) and its assigned ROI: blue = Focal M1 (channels at a 7.5 cm distance from the midline; primary ROI), green = dmM1 (combination of 1.5 and 4.5 cm bands), orange = vlM1 (combination of 10.5 and 12 cm bands). The shaded vertical bands in the background are added to visually highlight the approximate location of each ROI group; their widths are schematic and do not represent exact distance proportions.

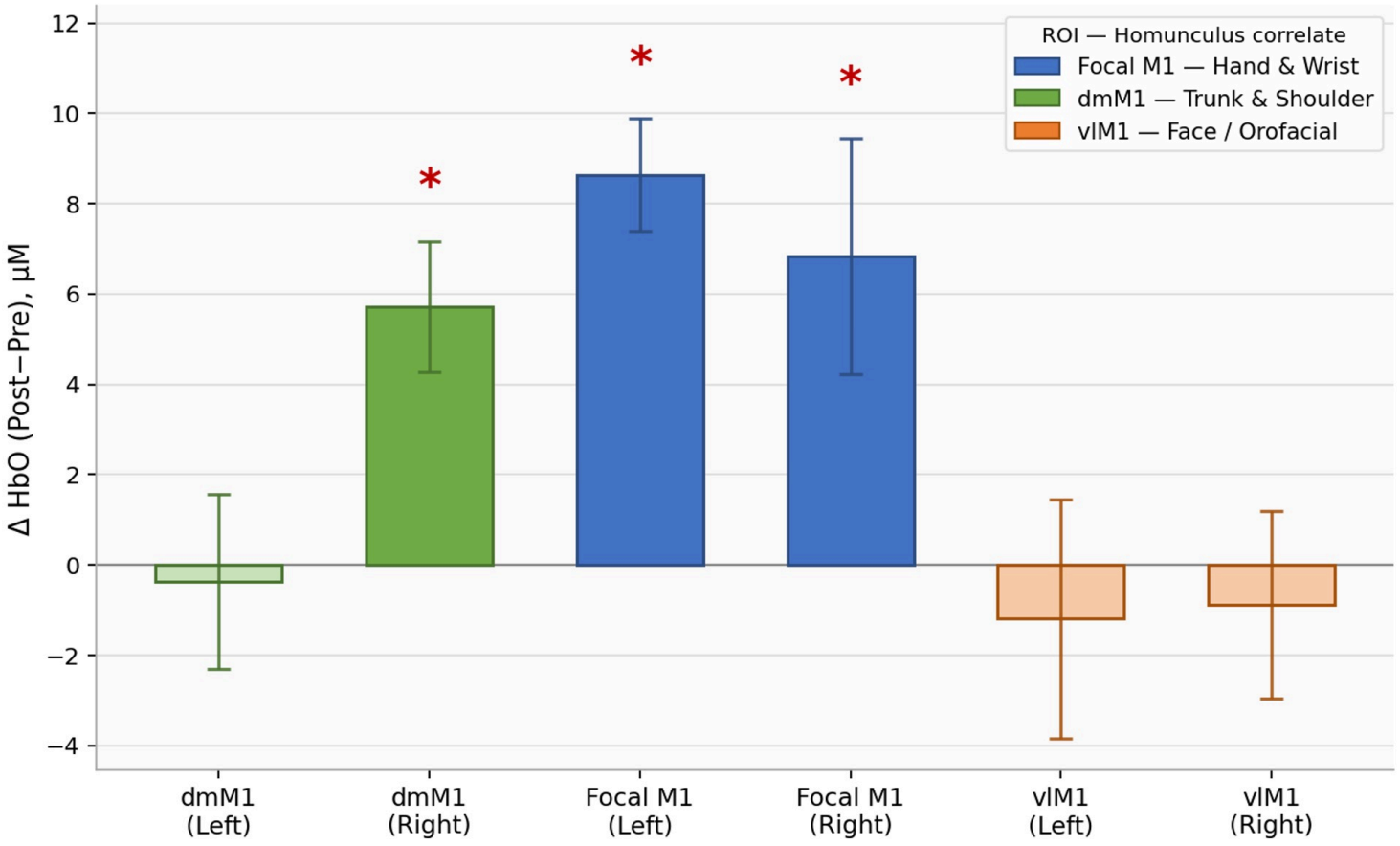


Figure 3

Pre-post HbO changes (Δ HbO) during the Motor Imagery (M) condition, presented separately for the left and right hemispheres. Bar colors denote the specific regions: blue for the Focal M1, green for the dmM1, and orange for the vlM1. The bars represent the Session (Post-test − Pre-test) fixed effect estimates (β, in µM) derived from the linear mixed-effects model, with error bars indicating the standard error (SE). Darker solid bars coupled with red asterisks (*) indicate statistically significant increases ($q < 0.05$) following the Benjamini-Hochberg (FDR) correction.

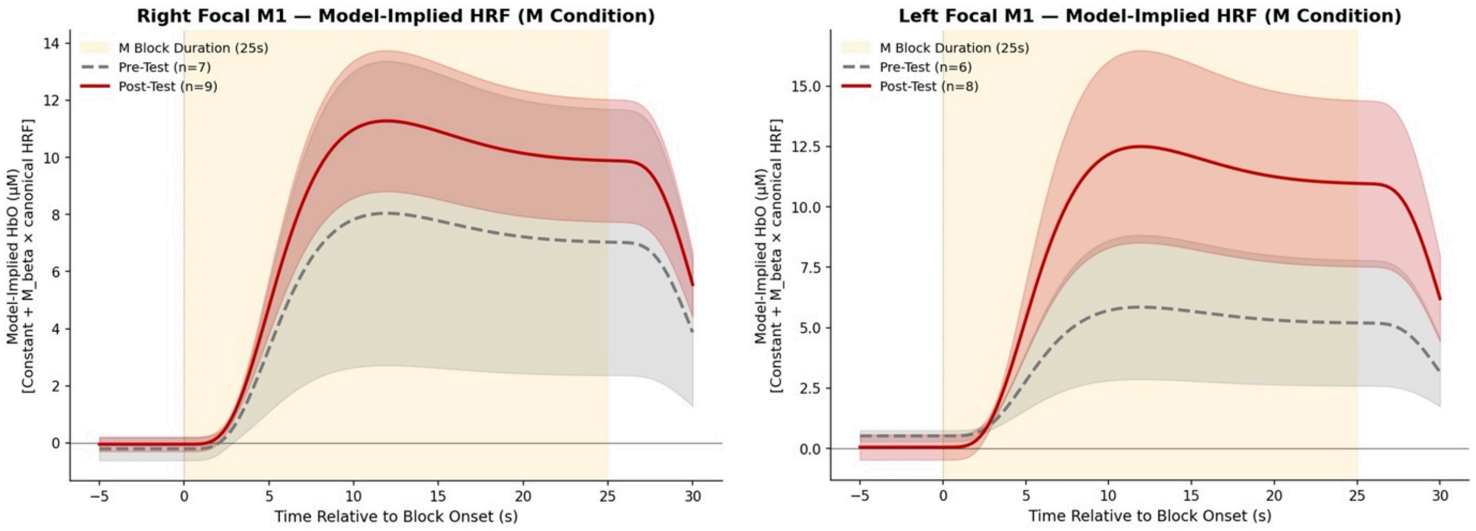


Figure 4

Model-implied hemodynamic response function (HRF) time courses during the Motor Imagery (M) condition for the (A) left and (B) right primary regions of interest (Focal M1). The temporal evolution of the signal was reconstructed for each participant by scaling the canonical double-gamma HRF (convolved with the 25-s block duration and peak-normalized) using the condition-specific amplitude (β) and baseline estimates derived from the General Linear Model. Solid red lines represent the group-averaged responses for the post-test session, and dashed gray lines represent the pre-test session. Shaded regions surrounding the curves indicate the inter-subject standard error (Left: Pre n=6, Post n=8; Right: Pre n=7, Post n=9). The shaded yellow background highlights the 25-s task duration starting from block onset (t=0). The linear trend term was excluded from this visualization due to its negligible effect within the short block window.

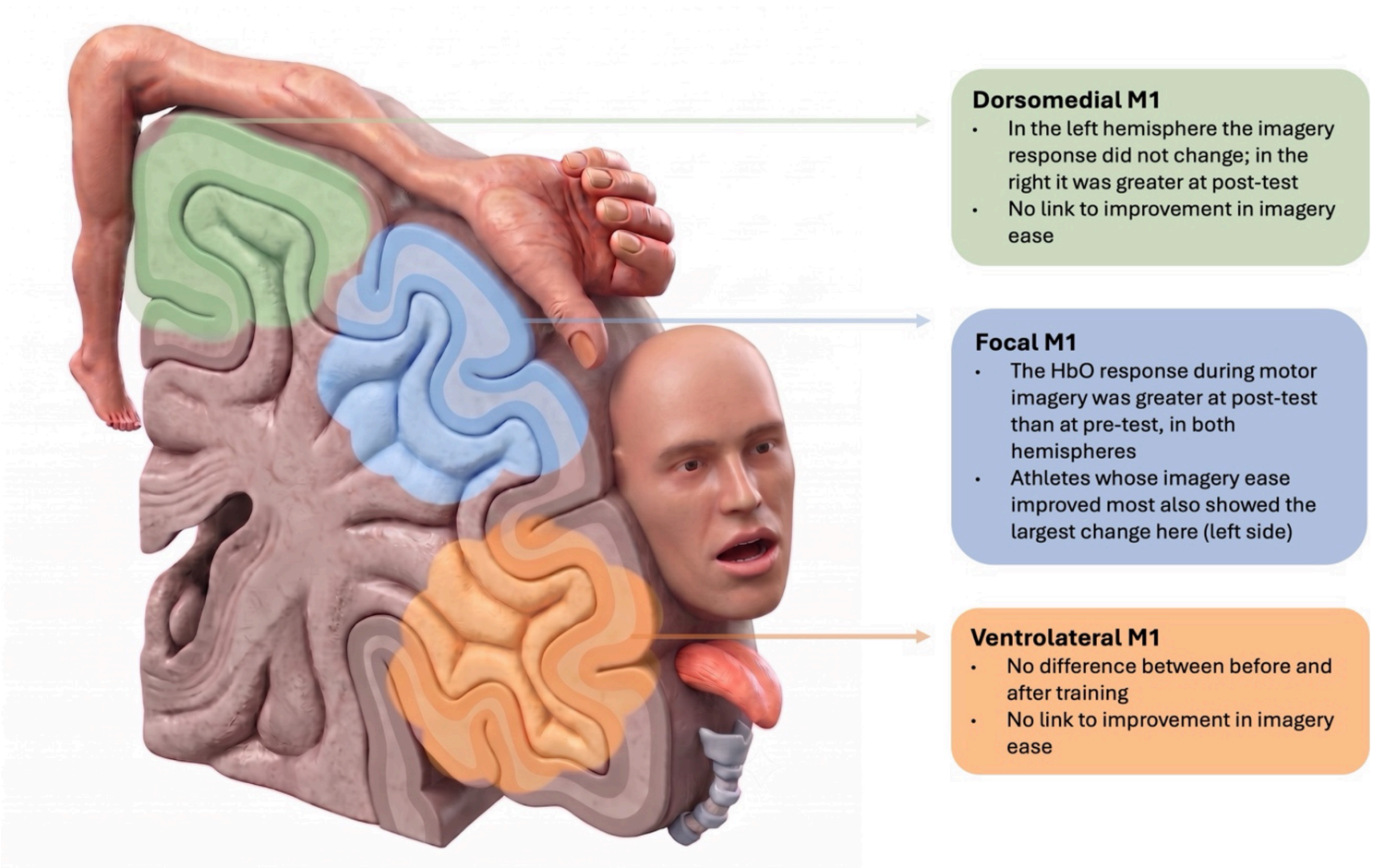


Figure 5

Schematic representation of the somatotopic organization of the primary motor cortex and motor homunculus illustrating the regional specificity of fNIRS hemodynamic adaptations following six weeks of motor imagery training. The target Focal M1 (blue) and adjacent dmM1 (green) regions exhibited significant training-induced HbO enhancements and contrast expansions, reflecting neuroplasticity related to the upper-limb/trunk-dominant spike serve. Conversely, the control vlM1 (orange) region

corresponding to orofacial representations showed no activation spread, confirming the strict spatial specificity of the training protocol.