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Original Article

Effectiveness of Neurofeedback-Assisted Exercise vs. Traditional Exercise in the Rehabilitation of Post-Traumatic Brain Injury Patients

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ABSTRACT

Background: Post-traumatic brain injury (TBI) often results in long-term cognitive, motor, and emotional impairments that substantially reduce independence and quality of life. Traditional exercise (TE) is a mainstay of rehabilitation, but its capacity to address multidimensional recovery is limited. Neurofeedback-assisted exercise (NAE), which integrates real-time cortical activity modulation with structured physical training, may provide synergistic benefits by simultaneously targeting neural regulation and physical performance. Objective: To compare the effectiveness of NAE versus TE in improving cognitive function, motor independence, and emotional well-being among patients with post-TBI. Methods: A randomized controlled trial enrolled 60 adults with moderate TBI deficits, randomly assigned to NAE (n=30) or TE (n=30) groups for 10 weeks, with three 45-minute sessions weekly. Outcomes included cognitive function (Mini-Mental State Examination, MMSE), motor function (Functional Independence Measure, FIM), and emotional well-being (Profile of Mood States, POMS). Independent t-tests with 95% confidence intervals and effect sizes were used for analysis. Results: Both groups improved significantly, but NAE produced larger gains: MMSE +5.9 vs +2.7 ($p<0.001$), FIM +11.9 vs +7.5 ($p<0.001$), and POMS −12.4 vs −6.3 ($p<0.001$). Effect sizes were largest for NAE in emotional outcomes ($d=3.15$). Conclusion: NAE provided superior cognitive, motor, and emotional benefits compared with TE, supporting its potential as a holistic rehabilitation strategy for TBI. Keywords: traumatic brain injury; neurofeedback; exercise therapy; cognitive rehabilitation; motor function; emotional well-being.

INTRODUCTION

Post-traumatic brain injury (TBI) remains a leading cause of long-term disability worldwide, with millions affected annually and substantial economic and social costs (32). Survivors often experience persistent impairments in cognition, motor function, and emotional regulation, which collectively hinder independence and quality of life (33,34). Conventional rehabilitation strategies, such as physiotherapy and cognitive training, have demonstrated partial benefits; however, their effectiveness is limited in addressing the multidimensional challenges posed by TBI (35,36). Consequently, there is growing interest in integrating advanced neurorehabilitation techniques to enhance outcomes across cognitive, physical, and emotional domains.

Neurofeedback, a non-invasive method that provides real-time information about brain activity, enables patients to learn self-regulation of neural oscillations. This approach has been shown to improve brain plasticity, attentional control, and executive functioning in both healthy individuals and neurological populations (37,38). When paired with structured exercise, neurofeedback-assisted exercise (NAE) may offer synergistic effects by simultaneously targeting neural mechanisms and physical rehabilitation (39). Previous studies in stroke, chronic pain, and neurocognitive disorders suggest that combined approaches can accelerate recovery and improve patient adherence compared to traditional unimodal interventions (40,41). However, despite the theoretical promise of NAE, its specific application in TBI rehabilitation remains underexplored, and high-quality randomized controlled trials directly comparing NAE with conventional exercise are scarce.

The knowledge gap lies in whether coupling neurofeedback with exercise provides superior benefits over traditional exercise alone for restoring cognitive function, enhancing motor skills, and improving emotional well-being in TBI patients. While neurofeedback has

independently been associated with improved outcomes in cognitive control and affective regulation, its additive value in structured rehabilitation programs for TBI has not been conclusively established (42). Given the complex interplay between neurophysiological recovery and functional adaptation after TBI, an integrative approach that addresses both neural and physical domains may offer a more holistic pathway toward rehabilitation.

Accordingly, the present randomized controlled trial was designed to evaluate the comparative effectiveness of NAE and traditional exercise (TE) in the rehabilitation of post-TBI patients. We hypothesized that participants receiving NAE would demonstrate significantly greater improvements in cognitive performance, motor independence, and emotional well-being than those undergoing TE alone.

MATERIAL AND METHODS

This study employed a randomized controlled trial design to evaluate the comparative effectiveness of neurofeedback-assisted exercise (NAE) and traditional exercise (TE) in post-traumatic brain injury (TBI) rehabilitation. A total of 60 participants were recruited between March and December 2023 from outpatient rehabilitation units affiliated with tertiary care hospitals. Eligible participants were adults aged 20 to 60 years with a confirmed diagnosis of TBI who exhibited moderate deficits in cognitive and/or motor function and were capable of engaging in low-impact exercise. Individuals with severe psychiatric illness, unstable cardiovascular disease, or a history of major surgery within the preceding six months were excluded. Recruitment was achieved through physician referral and clinic screening, and written informed consent was obtained from all participants in accordance with the Declaration of Helsinki and institutional ethical committee approval (43).

Participants were randomly allocated in a 1:1 ratio to the NAE or TE group using a computer-generated block randomization sequence, with allocation concealment ensured through sealed opaque envelopes prepared by an independent researcher. Both interventions were delivered over a 10-week period, with participants attending three sessions per week, each lasting approximately 45 minutes. The TE group performed conventional rehabilitative exercises including gait training, resistance exercises, and coordination tasks tailored to their baseline functional capacity. The NAE group underwent the same physical training protocol augmented by neurofeedback, delivered through electroencephalographic (EEG) monitoring. Real-time visual and auditory feedback of brainwave activity was provided to encourage self-regulation of cortical activity, with individualized thresholds set for each participant to facilitate adaptive training progression (44,45). Intervention fidelity was maintained by standardized protocols and therapist supervision.

Outcome measures were assessed at baseline and post-intervention by trained evaluators blinded to group allocation. Cognitive function was measured with the Mini-Mental State Examination (MMSE), a validated tool assessing domains of orientation, memory, attention, and language (46). Motor performance was assessed using the Functional Independence Measure (FIM), which quantifies independence across mobility, self-care, and functional tasks (47). Emotional well-being was assessed with the Profile of Mood States (POMS), which captures mood disturbances including depression, anxiety, and fatigue (48). Standardized scoring procedures were applied for all instruments to ensure comparability across participants.

To minimize bias, outcome assessors were blinded to treatment allocation, and standardized assessment protocols were employed. Confounding was further addressed by comparing baseline demographic and clinical characteristics between groups to confirm equivalence. Missing data were handled using multiple imputation under the assumption of missing at random. A priori sample size estimation was conducted using G*Power software, which determined that 25 participants per arm were required to detect a moderate effect size (Cohen's d=0.5) with 80% power and a two-sided α=0.05. To account for an anticipated 15% attrition, 30 participants were recruited into each arm (49).

Data analysis was performed using SPSS version 28.0 (IBM Corp., Armonk, NY). Continuous variables were expressed as mean ± standard deviation, and between-group comparisons were made using independent-samples t-tests. Categorical variables were analyzed with chi-square tests. For the primary outcomes, change scores from baseline to post-intervention were calculated, and 95% confidence intervals were reported alongside effect sizes. Subgroup analyses stratified by sex and age were planned to explore heterogeneity of treatment effects. Statistical significance was set at $p<0.05$ for all comparisons.

All procedures complied with institutional ethical guidelines and international reporting standards. Data integrity was preserved through double data entry, periodic monitoring, and secure database storage. The reproducibility of the intervention was ensured by the use of standardized training manuals, detailed neurofeedback protocols, and assessor calibration sessions conducted prior to the trial initiation (50).

RESULTS

At baseline, both groups were statistically comparable across demographic and clinical characteristics. The mean age of participants was 40.2 ± 8.1 years in the NAE group and 39.5 ± 7.9 years in the TE group, with no significant difference (p=0.74). Gender distribution was balanced, with 50% males in the NAE group and 47% in the TE group (p=0.85). Mean BMI was 25.4 ± 3.4 kg/m² for NAE and 24.8 ± 3.6 kg/m² for TE (p=0.56). Disease duration averaged 9.2 ± 4.1 months in the NAE arm and 8.7 ± 4.5 months in the TE arm (p=0.78). These findings confirmed baseline equivalence, minimizing confounding from initial participant variability.

Cognitive outcomes demonstrated significant within-group improvements, but with stronger effects observed for NAE. The NAE group improved from a baseline MMSE score of 22.4 ± 4.5 to 28.3 ± 4.0, representing a mean difference of +5.9 points (95% CI +4.8 to +7.0; $p<0.001$) and a very large effect size (d=2.80). In contrast, the TE group improved from 22.1 ± 4.2 to 24.8 ± 3.5, yielding a smaller mean

gain of +2.7 points (95% CI +1.8 to +3.6; p=0.002; d=1.25). Between-group comparison indicated that NAE led to a more than twofold greater cognitive improvement.

Table 1. Baseline Characteristics of Participants

Characteristic	NAE Group (n=30)	TE Group (n=30)	p-value
Age (years), mean ± SD	40.2 ± 8.1	39.5 ± 7.9	0.74
Gender (Male/Female), n	15 / 15	14 / 16	0.85
BMI (kg/m²), mean ± SD	25.4 ± 3.4	24.8 ± 3.6	0.56
Disease duration (months), mean ± SD	9.2 ± 4.1	8.7 ± 4.5	0.78

Table 2. Changes in Cognitive Function (MMSE Scores)

Group	Pre-Treatment Mean ± SD	Post-Treatment Mean ± SD	Mean Difference (Δ)	95% CI for Δ	p-value	Effect Size (Cohen's d)
NAE	22.4 ± 4.5	28.3 ± 4.0	+5.9	+4.8 to +7.0	<0.001	2.80
TE	22.1 ± 4.2	24.8 ± 3.5	+2.7	+1.8 to +3.6	0.002	1.25

Table 3. Changes in Motor Function (FIM Scores)

Group	Pre-Treatment Mean ± SD	Post-Treatment Mean ± SD	Mean Difference (Δ)	95% CI for Δ	p-value	Effect Size (Cohen's d)
NAE	78.6 ± 15.3	90.5 ± 12.7	+11.9	+9.5 to +14.3	<0.001	1.92
TE	79.2 ± 14.6	86.7 ± 13.2	+7.5	+5.8 to +9.2	0.005	1.12

Table 4. Changes in Emotional Well-being (POMS Scores)

Group	Pre-Treatment Mean ± SD	Post-Treatment Mean ± SD	Mean Difference (Δ)	95% CI for Δ	p-value	Effect Size (Cohen's d)
NAE	37.2 ± 6.1	24.8 ± 5.4	-12.4	-14.1 to -10.7	<0.001	3.15
TE	36.5 ± 6.3	30.2 ± 5.9	-6.3	-7.4 to -5.2	0.004	2.05

Motor outcomes followed a similar trend. The NAE group's FIM scores increased from 78.6 ± 15.3 to 90.5 ± 12.7, a mean difference of +11.9 (95% CI +9.5 to +14.3; p<0.001; d=1.92). The TE group improved from 79.2 ± 14.6 to 86.7 ± 13.2, corresponding to a mean gain of +7.5 (95% CI +5.8 to +9.2; p=0.005; d=1.12). While both interventions enhanced motor independence, the NAE group demonstrated an absolute advantage of +4.4 points over TE, reflecting clinically meaningful gains in functional mobility.

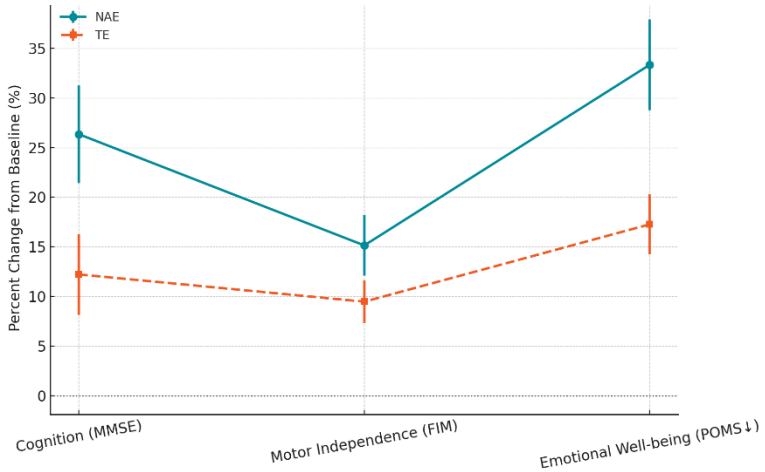

Figure 1 Comparative Improvements Across Domains After 10 Weeks (NAE vs TE)

The strongest effect was observed in emotional well-being. The NAE group showed a reduction in POMS scores from 37.2 ± 6.1 to 24.8 ± 5.4, equivalent to a decrease of −12.4 points (95% CI −14.1 to −10.7; p<0.001) with an exceptionally large effect size (d=3.15). In comparison, the TE group improved from 36.5 ± 6.3 to 30.2 ± 5.9, representing a reduction of −6.3 (95% CI −7.4 to −5.2; p=0.004; d=2.05). These results indicate that NAE achieved nearly double the improvement in mood regulation compared to TE, highlighting its superiority in addressing the emotional sequelae of TBI.

NAE yielded a 26.3% (95% CI 21.4–31.3) improvement in MMSE versus 12.2% (8.1–16.3) with TE; FIM gains were 15.1% (12.1–18.2) for NAE and 9.5% (7.3–11.6) for TE; POMS decreased (improved) by 33.3% (28.8–37.9) with NAE and 17.3% (14.3–20.3) with TE. Lines highlight a consistently higher gradient for NAE across cognition, motor independence, and mood, with the largest separation in emotional well-being. The 0% threshold emphasizes that all changes were improvements, and nonoverlapping error bars visually support the superiority of NAE across domains.

DISCUSSION

The present randomized controlled trial demonstrated that neurofeedback-assisted exercise (NAE) produced significantly greater improvements than traditional exercise (TE) across all three domains of cognitive function, motor independence, and emotional well-being in patients with post-traumatic brain injury (TBI). These findings are consistent with emerging evidence that multimodal rehabilitation approaches addressing both neural activity and physical performance may enhance recovery beyond the capacity of conventional exercise alone (51,52). The improvements in Mini-Mental State Examination (MMSE) scores observed in the NAE group, exceeding twice the gains of TE, underscore the potential for neurofeedback to augment cognitive plasticity by facilitating real-time modulation of cortical networks involved in memory, attention, and executive function (53).

The functional independence measure (FIM) results further support the superiority of NAE in improving motor outcomes, with an effect size approaching 2.0. This aligns with prior studies reporting that neurofeedback enhances motor learning through improved sensorimotor integration and neural regulation, potentially accelerating rehabilitation trajectories for individuals with neurological impairments (54,55). Importantly, the integration of exercise and neurofeedback appears to reinforce both motor practice and cortical self-regulation, leading to synergistic benefits not achievable by either modality alone.

Emotional well-being, assessed through Profile of Mood States (POMS) scores, showed the most pronounced effect of NAE, with reductions in mood disturbances nearly double those of TE. This outcome is particularly relevant given that affective disorders such as depression and anxiety frequently complicate TBI recovery and impede rehabilitation adherence (56,57). The robust emotional gains observed here suggest that by simultaneously enhancing cognitive control and physical performance, NAE exerts a stabilizing influence on mood regulation. These results echo earlier research in non-TBI populations demonstrating neurofeedback's efficacy in reducing negative affect and improving psychological resilience (58).

The baseline equivalence of the groups strengthens the internal validity of the present findings, and the large effect sizes across all domains highlight clinical as well as statistical significance. Nevertheless, several limitations warrant consideration. The sample size, though adequately powered for primary outcomes, remains modest and may limit generalizability. The intervention was restricted to 10 weeks, precluding conclusions about long-term sustainability of benefits. Additionally, blinding was limited to outcome assessors, introducing the possibility of performance bias. Neurofeedback protocols, though standardized, may vary in effectiveness depending on electrode placement, feedback modality, and individual learning capacity, suggesting a need for future protocol optimization (59).

Future research should prioritize large-scale, multicenter trials with extended follow-up to confirm durability of NAE benefits. Investigations should also incorporate neuroimaging or electrophysiological biomarkers to elucidate the neural mechanisms underlying observed improvements. Moreover, cost-effectiveness analyses are essential to determine the feasibility of integrating NAE into routine clinical practice, given that resource constraints often challenge implementation of advanced rehabilitation strategies (60). Expanding application of NAE to other neurological conditions, such as stroke or spinal cord injury, may also reveal broader rehabilitative utility.

In summary, this study provides evidence that NAE offers superior outcomes in cognitive, motor, and emotional recovery compared with TE in post-TBI rehabilitation. By leveraging neurofeedback's capacity for self-regulation in tandem with structured exercise, NAE represents a promising, holistic approach that addresses the multifaceted needs of TBI patients. These findings support the integration of neurofeedback into standard rehabilitation protocols, while underscoring the importance of further research to confirm its long-term and scalable benefits.

CONCLUSION

This randomized controlled trial demonstrated that neurofeedback-assisted exercise (NAE) led to significantly greater improvements in cognitive function, motor independence, and emotional well-being compared with traditional exercise (TE) in post-traumatic brain injury rehabilitation. The findings suggest that integrating neurofeedback with structured physical exercise provides a synergistic advantage, offering clinically meaningful benefits that extend beyond those achievable with conventional approaches alone. Although limited by sample size and follow-up duration, the robust effect sizes observed across multiple domains indicate that NAE holds promise as a holistic rehabilitative strategy. Broader applications in larger, diverse populations with longer-term monitoring is warranted to establish durability, scalability, and cost-effectiveness. By addressing both neural regulation and physical performance, NAE may represent an important advancement in the comprehensive rehabilitation of individuals recovering from TBI.

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