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A Comparative Study of the Effectiveness of Cognitive Behavioral Therapy With and Without Transcranial Stimulation on Sleep Quality in Patients with Musculoskeletal Pain

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ABSTRACT

The objective of this study was to compare the effectiveness of cognitive behavioral therapy (CBT) with and without transcranial stimulation on sleep quality in patients with musculoskeletal pain. This applied study employed a quasi-experimental pretest–posttest design with follow-up and a non-equivalent control group. The statistical population comprised all individuals with musculoskeletal pain diagnosed by an orthopedic specialist in Sirjan during 2024–2025. Using purposive non-random sampling, 45 participants were assigned into three groups: CBT combined with transcranial stimulation (n =15), CBT alone (n=15), and control (n=15). Each intervention followed structured protocols across multiple sessions. The Pittsburgh Sleep Quality Index (PSQI) was administered at pretest, posttest, and follow-up to assess outcomes. Data analysis was performed using repeated measures ANCOVA, supplemented by non-parametric tests when assumptions were not met. The results indicated that the overall model was statistically significant in predicting improvements in sleep quality ($F=14.943$, $p<0.001$, $\eta^2=0.657$). Group effects were highly significant ($F=36.917$, $p<0.001$, $\eta^2=0.654$), demonstrating that both experimental groups experienced substantial gains in sleep quality compared to the control group. Bonferroni post hoc tests revealed no significant difference between the two experimental groups ($p=1.000$), while both groups showed highly significant differences compared to the control group ($p<0.001$). These effects persisted at follow-up, confirming the stability of improvements over time. The study provides evidence that CBT is an effective and sustainable intervention for improving sleep quality among patients with musculoskeletal pain. While the addition of transcranial stimulation did not produce superior outcomes compared to CBT alone, both interventions significantly outperformed the control condition. These findings highlight CBT as a robust, non-pharmacological, and cost-effective therapeutic option for managing sleep disturbances in patients with chronic pain.

Keywords: Cognitive Behavioral Therapy; Transcranial Stimulation; Sleep Quality; Musculoskeletal Pain; Non-pharmacological Interventions

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Introduction

Musculoskeletal pain represents one of the most common health concerns worldwide, with significant effects on daily functioning, psychological well-being, and sleep quality. Chronic pain not only interferes with physical activity but also induces emotional distress and maladaptive behavioral responses that worsen patients' overall health outcomes. The persistence of sleep disturbances in individuals with musculoskeletal pain has been recognized as a critical factor that aggravates fatigue, reduces coping ability, and diminishes quality of life. Recent research has increasingly highlighted the role of psychological interventions such as cognitive behavioral therapy (CBT), alongside novel neuromodulatory methods like transcranial stimulation, as effective strategies to address both the physical and psychological dimensions of chronic pain and associated sleep disorders (1).

Sleep quality, in particular, has been widely studied due to its strong relationship with pain perception, emotional regulation, and cognitive performance. Poor sleep contributes to heightened pain sensitivity and lower thresholds for discomfort, creating a vicious cycle between insomnia and chronic pain syndromes. Numerous studies confirm that improving sleep quality leads to reductions in pain intensity, psychological distress, and functional disability among individuals suffering from chronic conditions (2). The relevance of CBT as a therapeutic modality stems from its capacity to simultaneously target maladaptive cognitions, emotional distress, and behavioral patterns that maintain both pain and sleep difficulties. In recent years, CBT has been adapted for various populations and health conditions, demonstrating consistent effectiveness in improving sleep quality, resilience, and overall well-being (3).

The evidence base supporting CBT in sleep-related disorders is substantial. For instance, digital and face-to-face CBT interventions for insomnia have been shown to significantly improve sleep quality across populations such as pregnant women (4), older adults (2), and clinical patients with anxiety (5). These findings align with studies confirming that structured CBT protocols are effective in reducing both psychological and physiological symptoms, ultimately leading to better sleep outcomes (6). In addition, CBT has been integrated with other supportive approaches, such as coping skills training or adjunctive light therapy, to enhance its impact on sleep and psychological functioning (7, 8).

CBT has been widely compared to other psychotherapies in terms of effectiveness on sleep-related issues. Several comparative studies have investigated CBT alongside acceptance and commitment therapy (ACT), mindfulness-based interventions, and cognitive-behavioral hypnotherapy. For example, evidence from research in women with fibromyalgia suggests that both CBT and CBT combined with hypnotherapy significantly improved sleep quality and resilience (3). Similarly, ACT and CBT have been contrasted in clinical populations such as mothers of children with learning disabilities (9), postmenopausal women experiencing sleep-related and sexual health problems (10), and patients with generalized anxiety disorder and irritable bowel syndrome (11). These studies consistently demonstrate that CBT is either comparable to or superior in enhancing sleep quality, depending on the target population and therapeutic context.

The increasing digitalization of healthcare delivery has extended the reach of CBT into web-based and internet-delivered platforms, providing greater accessibility to individuals suffering from insomnia or poor sleep. For example, internet-based CBT for insomnia has been found effective in student populations (12), as well as among individuals with multiple sclerosis who often suffer from sleep disruption (6). These digital approaches often include structured modules focusing on sleep hygiene, cognitive restructuring, and relaxation strategies. The digital transition of CBT interventions highlights not only its adaptability but also its potential for integration with other medical and psychosocial treatments.

The relevance of CBT in the context of musculoskeletal pain is particularly significant. Patients with chronic pain often develop maladaptive beliefs such as catastrophizing, avoidance behaviors, and negative emotional responses, all of which perpetuate both pain intensity and sleep difficulties. By targeting these patterns, CBT promotes adaptive coping, improved self-efficacy, and restoration of healthier sleep cycles (13). Indeed, empirical evidence shows that baseline sleep problems can predict treatment responsiveness, emphasizing the necessity of addressing sleep-related variables in chronic pain interventions.

Beyond traditional CBT, integration with other modalities such as neuromodulation offers an innovative approach. Transcranial stimulation, including transcranial direct current stimulation (tDCS) and related techniques, has shown promise in modulating cortical excitability, reducing pain perception, and enhancing sleep quality. For example, studies on acupressure and transcutaneous electrical acupoint stimulation have demonstrated significant benefits for fatigue, depression, and sleep among patients undergoing hemodialysis (14). Such findings suggest that combining CBT with brain stimulation may produce synergistic effects, simultaneously addressing cognitive-behavioral and neurophysiological mechanisms underlying sleep disruption and pain.

Recent systematic and clinical studies reinforce the importance of multi-dimensional approaches. Research on mindfulness-based interventions and CBT indicates their effectiveness in enhancing cognitive abilities and sleep quality among women with insomnia (15). Similarly, multisensory stimulation and cognitive rehabilitation have been found effective in addressing memory problems, mental states, and sleep disorders in older adults (16). Together, these studies highlight the diverse pathways through which non-pharmacological interventions can improve sleep, underscoring the role of CBT as a cornerstone therapy that can be combined with innovative techniques for enhanced outcomes.

From a broader perspective, CBT's adaptability to different populations—ranging from cancer patients (8), to adolescents (7), to elderly men in nursing homes (1)—illustrates its versatility and evidence-based effectiveness. In each context, the intervention is associated not only with improved sleep quality but also with enhanced mental health, emotional well-being, and daily functioning. The inclusion of sleep hygiene training, relaxation techniques, and cognitive restructuring within CBT protocols provides patients with practical strategies to manage both psychological and physiological aspects of sleep disturbance.

Importantly, cross-cultural evidence has validated CBT in both Western and non-Western contexts. Iranian studies, for example, have compared CBT with ACT in reducing indecision and improving sleep quality among patients with gastrointestinal disorders (11), or with mindfulness in women with insomnia (15). These studies suggest that CBT can be effectively adapted to diverse cultural backgrounds while retaining its therapeutic potency. At the same time, CBT is recognized as a cost-effective, non-invasive, and sustainable intervention that reduces reliance on pharmacological treatments, which often carry side effects and risks of dependency.

The clinical rationale for integrating CBT with transcranial stimulation in patients with musculoskeletal pain rests on complementary mechanisms of action. CBT works by modifying dysfunctional beliefs and behaviors, promoting healthier sleep practices, and improving emotional regulation, while transcranial stimulation directly modulates neural networks implicated in pain perception and sleep regulation (17). By combining these approaches, it is expected that patients will not only experience improvements in sleep quality but also in pain reduction, emotional well-being, and overall functionality. This combination represents an innovative strategy that bridges psychological and neurophysiological domains, aligning with the growing emphasis on integrative care models for chronic pain.

In summary, the literature strongly supports the role of CBT as an effective intervention for sleep quality across a variety of populations and conditions, with evidence of sustained improvements over time (4, 13). Furthermore, adjunctive methods such as transcranial stimulation have demonstrated promising effects in enhancing therapeutic outcomes for both sleep and pain (14). The integration of these interventions may therefore provide a comprehensive and innovative approach to addressing the multifaceted challenges of musculoskeletal pain and its associated sleep disturbances. Given the chronic nature of such conditions and their profound impact on patients' quality of life, exploring the comparative effectiveness of CBT with and without transcranial stimulation is both timely and clinically significant. The present study seeks to address this gap by systematically evaluating these interventions in a controlled experimental design, with the ultimate aim of contributing to improved evidence-based strategies for managing sleep quality in patients with musculoskeletal pain.

Methods and Materials

Study Design and Participants

The present study was applied in nature and employed a quasi-experimental design with a pretest–posttest and follow-up structure, along with a non-equivalent control group. The statistical population included all individuals diagnosed with musculoskeletal pain by an orthopedic specialist in Sirjan during the years 2024–2025. From this population, 50 participants suffering from musculoskeletal pain and attending orthopedic specialty clinics were selected using a non-random purposive sampling method. Participants were assigned into three groups: experimental group one (cognitive behavioral therapy combined with transcranial brain stimulation, 15 participants), experimental group two (cognitive behavioral therapy without transcranial brain stimulation, 15 participants), and a control group (15 participants). The required sample size was estimated based on similar previous studies, with an effect size of 0.40, a confidence level of 0.95, a statistical power of 0.80, and an anticipated attrition rate of 10%, leading to 15 participants per group. Considering the likelihood of participant dropouts based on prior research, attrition of up to five participants per group was projected, and thus the total sample was set at 45 individuals. The control group received only educational material without therapeutic intervention.

The inclusion criteria consisted of: confirmed diagnosis of musculoskeletal pain by a specialist for a minimum duration of three months, willingness and ability to regularly attend therapy sessions and collaborate throughout the study, provision of informed consent, age between 45 and 60 years (middle adulthood), basic literacy in reading and writing, and a history of chronic pain persisting for several years. The exclusion criteria included unwillingness to continue participation, receiving simultaneous treatments that could interfere with the current intervention, absence from more than three treatment sessions, previous hospitalization in psychiatric facilities, diagnosis of obsessive–compulsive disorder, participation in similar interventions, or enrollment in other training or counseling programs during the study period.

Data Collection

The Pittsburgh Sleep Quality Index (PSQI), developed by Buysse and colleagues in 1989, was used as the main tool to assess sleep quality and to differentiate between good and poor sleepers. The instrument consists of 18 items that are categorized into seven components. The first component evaluates subjective sleep quality, assessed by item 9. The second component measures sleep latency, calculated from the mean of item 2 and part A of item 5. The third component assesses sleep duration through item 4. The fourth component, sleep efficiency, is calculated as the ratio of total hours slept to total hours spent in bed multiplied by 100. The fifth component relates to sleep disturbances and is determined by the mean scores of item 5. The sixth component examines the use of sleep medications, assessed by item 6. The seventh component evaluates daytime dysfunction, which is calculated from the mean of items 7 and 8. Each item is rated on a scale ranging from 0 to 3, and the total score is obtained by summing the means of all seven components, yielding a range between 0 and 21. Higher scores indicate poorer sleep quality, and a global score greater than 6 is considered indicative of undesirable sleep quality. Previous studies have examined the psychometric properties of the PSQI in Iran, reporting a Cronbach's alpha coefficient of 0.89 and a correlation reliability of 0.88, which confirm the reliability and validity of the instrument for use in the present study.

Interventions

The cognitive behavioral therapy pain management intervention was conducted over 12 structured sessions based on the protocol of Macfarlane et al. (2016), designed to reduce disability from musculoskeletal pain and improve psychological distress, functional limitations, and sleep quality. Sessions were delivered in groups twice weekly, each lasting approximately one hour, and facilitated face-to-face by the researcher. The program began with establishing rapport, completing baseline pain assessment tools, and initiating a daily pain diary. Subsequent sessions introduced participants to theories of pain, such as the gate control model, and the role of thoughts and emotions in pain perception. Participants learned to identify and record negative thoughts, apply cognitive restructuring techniques, and transform maladaptive cognitions into adaptive alternatives. Anger recognition and management strategies were addressed through psychoeducation and practical exercises. Psychological helplessness and its emotional impact were explored through group discussions and reflective writing tasks. Dedicated sessions on sleep hygiene and relaxation techniques aimed to improve sleep quality. Activity pacing and gradual re-engagement in daily routines were encouraged through goal setting and behavioral activation. Participants tested misbeliefs about pain through behavioral experiments and evaluated their outcomes. Relapse prevention strategies were introduced to identify triggers and develop coping plans. Progress was monitored by comparing baseline and follow-up results, culminating in a summary session where participants reflected on achievements and developed future action plans to sustain skills. Each session included structured methods, discussions, and home assignments, ensuring that participants engaged actively in the therapeutic process and integrated strategies into daily life.

The transcranial direct current stimulation intervention was administered using a German-made NeuroConn device equipped with two electrodes. The anodal electrode was positioned over the left dorsolateral prefrontal cortex (DLPFC) at the PF3 site according to the 10/20 EEG system, while the cathodal electrode was placed over the contralateral supraorbital area. Across 20 treatment sessions, stimulation was applied to target neural circuits related to social cognition, guidance, emotional regulation, and affective responses to others. To address pain reduction and associated disability, additional electrode montages involved placing the anodal electrode over the primary motor cortex (M1) at sites C3 or C4, with the cathode positioned on the shoulder to optimize current flow and reduce musculoskeletal pain perception. Furthermore, specific placements such as anodal electrodes at T4, T6, and P4 sites were used to modulate parietal and temporal regions involved in sensory and emotional processing. The structured application of tDCS sessions aimed to enhance the effectiveness of cognitive-behavioral interventions by modulating cortical excitability, improving pain regulation mechanisms, and strengthening emotional and behavioral control pathways.

Data Analysis

The collected data were analyzed using both descriptive and inferential statistical methods. Descriptive analysis was conducted to organize and summarize the data, including the calculation of mean, standard deviation, skewness, kurtosis, and the Shapiro–Wilk test to assess normality of distributions. When the assumption of normality was met, hypotheses were tested using repeated measures analysis of covariance (ANCOVA) with the aid of SPSS version 26. In cases where the normality assumption was violated, data transformations such as square root transformation were initially attempted. If the issue remained unresolved, non-parametric alternatives were used, including Friedman's repeated measures test within groups and the Kruskal–Wallis test to compare groups at different stages. These procedures ensured that the statistical conclusions were robust regardless of the distributional characteristics of the data.

Findings and Results

The demographic characteristics of the study participants indicated that the age distribution across groups was relatively balanced. In the cognitive behavioral therapy with transcranial stimulation group, 4 participants (8.8%) were between 45 and 50 years, 6 participants (13.3%) were between 51 and 55 years, and 5 participants (11.1%) were between 56 and 60 years. In the cognitive behavioral therapy without stimulation group, 2 participants (4.4%) were aged 45–50 years, 7 participants (15.5%) were aged 51–55 years, and 6 participants (13.3%) were aged 56–60 years. In the control group, 1 participant (2.2%) was aged 45–50 years, 8 participants (17.6%) were aged 51–55 years, and 6 participants (13.3%) were aged 56–60 years. Regarding gender, the cognitive behavioral therapy with stimulation group consisted of 9 women (20%) and 6 men (13.3%), the therapy without stimulation group included 8 women (17.6%) and 7 men (15.5%), and the control group comprised 10 women (22.2%) and 5 men (11.4%). With respect to educational attainment, in the therapy with stimulation group, 11 participants (20.8%) held a high school diploma, 3 participants (6.6%) had a bachelor's degree, and 1 participant (2.2%) had a master's degree. In the therapy without stimulation group, 10 participants (22.2%) held a high school diploma and 5 participants (11.4%) had a bachelor's degree, while none held a master's degree. In the control group, 9 participants (20%) had a diploma, 5 participants (11.4%) had a bachelor's degree, and 1 participant (2.2%) held a master's degree. Overall, the distribution of demographic variables suggests that the groups were relatively comparable in terms of age, gender, and educational level, supporting the validity of subsequent group comparisons.

Table 1. Mean and Standard Deviation of Research Variables in Experimental and Control Groups

Variable	Group	Pre-test (M ± SD)	Post-test (M ± SD)	Follow-up (M ± SD)
Sleep Quality	CBT with Transcranial Stimulation	15.60 ± 2.31	26.70 ± 1.49	26.90 ± 1.59
	CBT without Transcranial Stimulation	16.80 ± 2.20	25.90 ± 1.10	26.26 ± 1.33
	Control	16.69 ± 1.82	16.70 ± 1.41	16.20 ± 1.98

The results presented in Table 1 indicate clear differences in sleep quality between the experimental and control groups over the course of the intervention and follow-up. At the pre-test stage, mean scores of sleep quality were similar across the three groups, suggesting initial comparability of baseline conditions. However, by the post-test, both experimental groups that received cognitive behavioral therapy, with and without transcranial stimulation, showed significant increases in mean sleep quality scores compared to the control group. Specifically, the group receiving CBT combined with transcranial stimulation improved from a mean of 15.60 at pre-test to 26.70 at post-test, while the CBT-only group improved from 16.80 to 25.90. These gains were maintained at the follow-up stage, with means of 26.90 and 26.26 respectively, reflecting stability of therapeutic effects over time. In contrast, the control group demonstrated no meaningful changes, with mean scores remaining nearly constant from pre-test (16.69) to post-test (16.70) and showing a slight decline at follow-up (16.20). The standard deviations also indicate relatively low variability in the post-test and follow-up measurements for the experimental groups, reinforcing the consistency of the observed improvements. Overall, these findings demonstrate that cognitive behavioral therapy, particularly when combined with transcranial stimulation, produced substantial and sustained improvements in sleep quality among patients with musculoskeletal pain, while no such improvements were evident in the control group.

Before conducting the main analyses, the statistical assumptions underlying the chosen methods were carefully examined. The normality of data distribution was assessed using the Shapiro–Wilk test, and the results indicated that the distributions of the study variables did not significantly deviate from normality in the pre-test, post-test, and follow-up phases. Homogeneity of variances across groups was verified through Levene's test, which confirmed that error variances were equal and thus comparable. Additionally, the assumption of sphericity, required for repeated measures analysis, was evaluated using Mauchly's test and was found to be satisfactory. In cases where minor deviations from normality were observed, appropriate data transformations were applied, ensuring that the assumptions for parametric tests were adequately met. Taken together, these checks confirmed that the assumptions of normality, homogeneity, and sphericity were satisfied, thereby validating the use of repeated measures ANCOVA for hypothesis testing in this study.

Table 2. Results of ANCOVA and Linearity of the Effect of Educational Groups

Effect	Variable	Sum of Squares	df	Mean Square	F	Sig.	Eta Squared
Corrected Model	Sleep Quality	8529.652	5	1705.93	14.943	0.000	0.657
Intercept (Constant)	Sleep Quality	2103.719	1	2103.719	18.428	0.000	0.321
Group	Sleep Quality	8248.967	2	4214.484	36.917	0.000	0.654
Error	Sleep Quality	4452.259	39	114.160			
Total	Sleep Quality	314415	45				
Corrected Total	Sleep Quality	12981.911	44				

The analysis of covariance (ANCOVA) results, as presented in Table 2, demonstrate that the applied model was statistically significant in explaining differences in sleep quality among the groups. The corrected model yielded an F-value of 14.943 with a significance level of $p < 0.001$ and an effect size (Eta squared) of 0.657, indicating that approximately 66% of the variance in sleep quality could be explained by the model. The fixed effect (intercept) was also significant ($F = 18.428$, $p < 0.001$), confirming the stability of baseline differences across measurements. Most importantly, the group effect was highly significant ($F = 36.917$, $p < 0.001$), with an Eta squared value of 0.654, reflecting a large effect size and confirming that the type of intervention produced substantial differences in sleep quality outcomes. The error term was relatively small compared to the explained variance, supporting the robustness of the findings. Overall, these results confirm that cognitive behavioral therapy, with and without transcranial stimulation, significantly improved sleep quality compared to the control group, and the effect of the interventions accounted for a considerable proportion of variance in the outcome variable.

Table 3. Bonferroni Post Hoc Test Results

Variable	Stage	Group (I)	Group (J)	Std. Error	Sig.
Sleep Quality	Post-test	CBT with Transcranial Stimulation	CBT without Stimulation	1.27	1.000
		CBT with Transcranial Stimulation	Control	1.27	0.000
		CBT without Stimulation	CBT with Transcranial Stimulation	1.27	1.000
		CBT without Stimulation	Control	1.27	0.000
		Control	CBT with Transcranial Stimulation	1.27	0.000
		Control	CBT without Stimulation	1.27	0.000
Sleep Quality	Follow-up	CBT with Transcranial Stimulation	CBT without Stimulation	3.43	1.000
		CBT with Transcranial Stimulation	Control	3.43	0.000
		CBT without Stimulation	CBT with Transcranial Stimulation	3.43	1.000
		CBT without Stimulation	Control	3.43	0.000
		Control	CBT with Transcranial Stimulation	3.43	0.000
		Control	CBT without Stimulation	3.43	0.000

The Bonferroni post hoc comparisons presented in Table 3 reveal that at both the post-test and follow-up stages, there was no significant difference in sleep quality improvements between the two experimental groups (CBT with transcranial stimulation versus CBT without stimulation), as all comparisons yielded non-significant results ($p = 1.000$). However, both experimental groups showed highly significant improvements in sleep quality compared to the control group at the post-test ($p < 0.001$) and follow-up ($p < 0.001$). This pattern demonstrates that cognitive behavioral therapy, whether administered alone or in combination with transcranial stimulation, was effective in significantly enhancing sleep quality in patients with musculoskeletal pain, while the control group exhibited no improvement. The lack of difference between the two intervention groups suggests that the core therapeutic effect was primarily attributable to the cognitive behavioral therapy itself, although both forms were equally effective in sustaining improvements over time.

Discussion and Conclusion

The findings of the present study demonstrate that both cognitive behavioral therapy (CBT) alone and CBT combined with transcranial stimulation significantly improved sleep quality in patients with musculoskeletal pain, compared to a control group that received no active intervention. Improvements observed in the experimental groups were not only substantial immediately after the intervention but also sustained at the follow-up stage. This pattern highlights the effectiveness of structured CBT-based interventions in addressing chronic sleep difficulties associated with pain disorders, while also pointing to the potential benefits of combining psychological and neurophysiological methods. Interestingly, the results revealed no statistically significant difference between the two intervention groups, suggesting that CBT itself provides a robust therapeutic impact that is not necessarily enhanced by the addition of transcranial stimulation.

The observed improvements in sleep quality are consistent with a wide body of research demonstrating CBT's efficacy in targeting insomnia and sleep disturbances across different clinical populations. For instance, a randomized trial on older adults found that CBT-based training programs were effective in improving sleep quality and mental health, corroborating the present findings that such interventions can bring measurable benefits to sleep even in individuals with complex health conditions (1, 2). Similarly, studies on patients with fibromyalgia syndrome indicated that CBT alone or in combination with hypnotherapy improved resilience and sleep quality, lending support to the notion that structured psychological therapy is powerful in reducing sleep-related dysfunctions in populations with chronic pain (3).

The sustainability of the improvements observed at follow-up reflects the enduring benefits of CBT interventions. Digital and in-person CBT protocols for insomnia have been shown to produce long-lasting effects, as demonstrated in trials with pregnant women (4), individuals with multiple sclerosis (6), and adolescents (7). These studies support the robustness of CBT as a therapeutic approach that not only initiates change but also equips patients with long-term coping skills. This aligns with the current study's follow-up results, where patients retained their improvements weeks after the conclusion of therapy.

The finding that CBT combined with transcranial stimulation did not outperform CBT alone requires nuanced interpretation. Although transcranial stimulation has demonstrated potential benefits in modulating cortical activity, reducing fatigue, and improving sleep quality—as seen in studies on acupressure and transcutaneous stimulation for hemodialysis patients (14)—the present study indicates that these effects may not add significant value when CBT is already in place. One explanation could be that CBT directly targets the maladaptive cognitions and behaviors central to both pain and sleep disturbances, thereby producing a sufficiently large effect size that additional physiological stimulation cannot enhance in a meaningful way. Another possibility is that the dosage, electrode placement, or session design of the stimulation in this study may not have optimized its potential synergistic effect with CBT. Future investigations could explore alternative stimulation parameters or populations with more severe sleep dysfunction to evaluate whether additive effects emerge under different conditions.

Nevertheless, the present study underscores the value of CBT as a versatile and evidence-based intervention. Numerous comparative studies have illustrated CBT's superiority or comparability to other modalities, including acceptance and commitment therapy (ACT) and mindfulness-based interventions. For example, research on mothers of children with learning disabilities demonstrated that CBT and ACT both improved sleep and quality of life (9). Likewise, studies on postmenopausal women found CBT effective in reducing mood swings and enhancing sleep quality (10), while in patients with generalized anxiety disorder, CBT outperformed or complemented ACT in improving sleep (11). These consistent findings position CBT as a core intervention for diverse groups facing both psychological and somatic challenges.

Digital and internet-based adaptations of CBT further reinforce its applicability and relevance. Recent protocols with student populations highlight the role of web-based CBT and sleep hygiene education in improving not only sleep quality but also executive functioning (12). Other studies have extended CBT to cancer patients, demonstrating its effectiveness in improving sleep alongside reductions in depression and anxiety (8). Collectively, these findings echo the outcomes of the present study and confirm that CBT provides a highly adaptable therapeutic framework across varied health settings.

Another important dimension of this study is its contribution to the literature on chronic musculoskeletal pain, a condition often accompanied by maladaptive cognitions and behaviors such as catastrophizing, avoidance, and hopelessness. Sleep disturbance in this population exacerbates pain sensitivity and lowers coping resources, creating a self-perpetuating cycle. The improvements observed in the current study align with findings showing that CBT helps break this cycle by restructuring maladaptive cognitions, encouraging adaptive coping strategies, and promoting behavioral activation (13). Moreover, baseline sleep difficulties have been found to predict responsiveness to CBT, which may explain why participants in the present study showed significant gains after treatment.

Furthermore, the study contributes to the growing recognition of multidimensional, non-pharmacological approaches to sleep and pain management. Research integrating multisensory stimulation and cognitive rehabilitation for older adults has demonstrated improvements in sleep and cognitive outcomes (16). Similarly, mindfulness-based and CBT interventions targeting women with insomnia have shown benefits for both sleep quality and cognitive performance (15). These convergent findings illustrate the versatility of CBT and its compatibility with other approaches, though the current study suggests that its standalone impact remains substantial.

Taken together, the results reinforce several critical conclusions. First, CBT is a robust and effective therapy for improving sleep quality among individuals with musculoskeletal pain. Second, although transcranial stimulation shows potential in other contexts, its combination with CBT in this study did not confer additional benefits, raising important questions about optimal design and application. Third, the sustained improvements at follow-up highlight CBT's capacity to produce lasting changes, consistent with evidence from prior literature across diverse populations. Finally, the findings emphasize the importance of integrating psychological interventions into standard care for chronic pain and sleep disorders, as they offer safe, non-invasive, and cost-effective solutions compared to pharmacological treatments.

Despite the promising results, this study is subject to several limitations that must be acknowledged. The first limitation concerns the relatively small sample size, which, although statistically adequate based on power calculations, limits the generalizability of the findings to broader populations. A larger and more diverse sample would provide greater external validity and allow subgroup analyses, such as examining gender or age-related differences in response to treatment. Second, the study relied exclusively on self-reported measures of sleep quality, which, while validated and reliable, may be influenced by subjective biases. The inclusion of objective sleep measures such as actigraphy or polysomnography would strengthen the conclusions. Third, the quasi-experimental design with non-randomized group allocation may have introduced selection bias, as participants were recruited purposively rather than randomly assigned. Although baseline comparability was established, unmeasured variables could have influenced treatment outcomes. Additionally, the intervention duration and stimulation parameters may not have been sufficient to detect the full potential of transcranial stimulation. Finally, the study was conducted in a single city, which limits cultural and contextual diversity, and follow-up assessments were limited to the short term, leaving long-term sustainability of effects uncertain.

Future studies should aim to address these limitations by employing randomized controlled trial designs with larger and more heterogeneous samples to enhance generalizability. The use of multimodal assessment methods, including both subjective and objective measures of sleep, would provide a more comprehensive understanding of intervention outcomes. Research should also explore the differential effects of CBT and combined interventions across specific subgroups, such as individuals with severe insomnia, different musculoskeletal conditions, or comorbid psychiatric disorders. Further, future work should experiment with different parameters of transcranial stimulation, including intensity, frequency, electrode placement, and duration, to optimize its integration with CBT. Long-term follow-ups extending several months or even years would be valuable to assess the persistence of treatment effects. Comparative studies between CBT, pharmacological treatments, and integrative approaches could provide insights into the most effective, safe, and cost-efficient management strategies. Finally, given the increasing importance of technology in healthcare delivery, future research should examine the effectiveness of digital and hybrid CBT combined with neuromodulation, expanding accessibility for patients unable to attend face-to-face sessions.

The findings of this study carry several practical implications for clinical practice. Health professionals working with patients suffering from musculoskeletal pain should incorporate CBT into their treatment plans, as it has demonstrated strong effectiveness in improving sleep quality and overall well-being. CBT protocols can be delivered individually or in groups and can be adapted for diverse healthcare settings, including rehabilitation centers, hospitals, and community clinics. While transcranial stimulation did not yield additional benefits in this study, clinicians may still consider it in specific cases, particularly for patients unresponsive to CBT alone or with severe sleep disturbances, provided that stimulation parameters are optimized. Training healthcare providers in CBT techniques and integrating sleep-focused interventions into routine pain management could reduce reliance on medication, improve patient outcomes, and lower healthcare costs. Policymakers and healthcare systems should prioritize the availability and dissemination of CBT-based interventions as evidence-based practices for sleep and pain management.

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Authors' Contributions

All authors equally contributed to this study.

Declaration of Interest

The authors of this article declared no conflict of interest.

Ethical Considerations

The study protocol adhered to the principles outlined in the Helsinki Declaration, which provides guidelines for ethical research involving human participants.

Transparency of Data

In accordance with the principles of transparency and open research, we declare that all data and materials used in this study are available upon request.

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