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How Does Exercise Improve Executive Function During Recovery from Major Depressive Disorder? A Narrative Review

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Abstract
Background: Major Depressive Disorder (MDD) is frequently associated with persistent cognitive deficits that often remain despite remission of depressive symptoms. Executive dysfunction, including impairments in working memory, inhibitory control, cognitive flexibility, planning, and decision-making, contributes to poorer psychosocial functioning and increased relapse risk. Although exercise is an established treatment for depression, its role in restoring executive functioning remains less well understood.
Objective: This narrative review evaluated current evidence on the effects of exercise on executive function recovery in individuals with MDD, identified exercise characteristics associated with the greatest cognitive benefits, and summarized the underlying neurobiological mechanisms.
Methods: A structured narrative review was conducted using PubMed, Scopus, and Web of Science. Priority was given to systematic reviews, meta-analyses, randomized controlled trials, and mechanistic studies investigating exercise, executive functioning, and neurobiological adaptations relevant to MDD.
Results: Structured exercise consistently improved executive functioning in individuals recovering from MDD. The greatest benefits were observed following moderate-to-vigorous aerobic exercise performed approximately three times per week, with sessions lasting 45–60 minutes for at least 13 weeks. Improvements were associated with enhanced neuroplasticity, reduced neuroinflammation, improved cerebral perfusion, neurotransmitter modulation, mitochondrial adaptations, and functional brain network reorganization.
Conclusions: Structured exercise should be regarded as a mechanism-based intervention that extends beyond symptom reduction by promoting executive function recovery and long-term functional rehabilitation. We propose an Integrated Exercise–Neurobiology Model linking

exercise prescription with coordinated physiological and neurobiological adaptations that may guide future mechanistic research and precision exercise interventions.

Keywords: Major Depressive Disorder; depression; exercise; executive function; cognitive rehabilitation; neuroplasticity; exercise prescription; precision exercise medicine.

1. Introduction

Major Depressive Disorder (MDD) is one of the leading contributors to disability worldwide and represents a major public health challenge [1]. According to the World Health Organization, approximately 332 million people are currently living with depression, making it one of the most prevalent psychiatric disorders and a substantial source of individual, societal, and economic burden [1]. Although advances in pharmacological and psychological therapies have substantially improved the management of depressive symptoms, complete recovery remains difficult to achieve for many individuals [1]. Increasing evidence suggests that successful treatment should not be defined solely by symptomatic remission but also by the restoration of cognitive, occupational, and psychosocial functioning [2].

This shift from symptomatic remission to functional recovery has become one of the defining developments in contemporary psychiatry [2]. Many individuals who no longer meet the diagnostic criteria for depression continue to experience persistent impairments in everyday functioning, including difficulties returning to work, maintaining interpersonal relationships, and managing complex daily activities. These limitations are increasingly attributed to residual cognitive dysfunction rather than persistent mood symptoms alone [2,9]. Accordingly, cognitive recovery has emerged as a key therapeutic objective during rehabilitation from MDD [2].

Among the cognitive domains affected by depression, executive functions appear to play a particularly important role in determining long-term outcomes. They comprise higher-order cognitive processes responsible for planning, working memory, inhibitory control, cognitive flexibility, decision-making, problem solving, and goal-directed behaviour [3]. These functions enable individuals to regulate behaviour, adapt to changing environmental demands, suppress inappropriate responses, and successfully perform complex cognitive tasks [3]. Numerous studies have demonstrated that executive dysfunction is associated with poorer occupational performance, reduced treatment adherence, diminished quality of life, and an increased risk of depressive relapse [4,5]. Moreover, executive dysfunction frequently persists despite substantial improvement in depressive symptoms, suggesting that cognitive recovery follows a trajectory distinct from emotional recovery [4,5].

Given the central role of executive functioning in maintaining functional independence, interventions capable of restoring these cognitive processes have attracted increasing scientific interest. During the past decade, exercise has emerged as one of the most promising non-pharmacological strategies for improving both mental and cognitive health [6]. Beyond its well-established antidepressant effects, structured exercise has consistently been associated with improvements in executive functioning, memory, attention, and global cognitive performance across both clinical and healthy populations [7,8]. Collectively, these findings have expanded the role of exercise from a general lifestyle recommendation to an evidence-informed therapeutic intervention.

From the perspective of exercise science, this shift carries important clinical implications. Exercise professionals are increasingly involved in multidisciplinary rehabilitation programmes for individuals with chronic neurological and psychiatric disorders. Consequently, understanding how exercise influences executive functioning extends beyond symptom management and has direct relevance for clinical practice. Identifying the characteristics of exercise prescription that maximize cognitive recovery may assist clinicians, physiotherapists, exercise physiologists, and other healthcare professionals in designing interventions that improve not only physical fitness but also cognitive and functional outcomes.

Despite the rapidly expanding body of evidence supporting the cognitive benefits of exercise, several important questions remain unanswered. Existing reviews have primarily focused either on the antidepressant effects of exercise or on general cognitive performance, whereas relatively few have specifically examined executive function recovery during rehabilitation from MDD. Likewise, although multiple neurobiological mechanisms—including enhanced neuroplasticity, reduced neuroinflammation, improved neurotransmitter regulation, increased cerebral perfusion, mitochondrial adaptations, and large-scale functional brain network reorganization—have been proposed, they are typically discussed in isolation rather than integrated into a unified biological framework [7].

Addressing these knowledge gaps is particularly important because optimizing exercise prescription requires an understanding of both whether exercise improves executive functioning and the biological mechanisms through which these improvements occur. A clearer understanding of these pathways may facilitate the development of more precise exercise prescriptions and further advance the emerging field of mechanism-based exercise medicine.

Therefore, the present narrative review has three primary objectives: (1) to evaluate the current evidence regarding the effects of exercise on executive function recovery in individuals with Major Depressive Disorder; (2) to identify the characteristics of exercise interventions associated with the greatest cognitive benefits; and (3) to synthesize current knowledge regarding the neurobiological mechanisms that may explain exercise-induced improvements in executive functioning. By integrating clinical evidence with contemporary findings from neuroscience and exercise physiology, this review proposes an **Integrated Exercise–Neurobiology Model of Executive Function Recovery**, providing a conceptual framework that links exercise prescription with coordinated biological adaptations, executive function recovery, and long-term functional outcomes in individuals recovering from Major Depressive Disorder.

2. Methods

2.1 Literature Search Strategy

A narrative review was conducted to synthesize the available evidence regarding the effects of exercise on executive function recovery in individuals with Major Depressive Disorder (MDD). Although narrative reviews do not require the methodological rigor of systematic reviews, a structured literature search strategy was adopted to enhance transparency, minimize selection bias, and ensure comprehensive coverage of the available evidence [10]. The review was designed to identify and critically evaluate studies investigating both the clinical effects of exercise on executive functioning and the neurobiological mechanisms that may underlie these effects.

Electronic searches were conducted using **PubMed, Scopus, and Web of Science**, which collectively provide comprehensive coverage of research in biomedicine, neuroscience, psychiatry, and exercise science. Eligible studies were published between **January 2015 and July 2026**, with database searches performed in **July 2026** to incorporate the most recent advances in exercise neuroscience and depression research. Earlier landmark publications were included when they provided essential theoretical or mechanistic foundations, particularly in the areas of neuroplasticity, executive functioning, and exercise physiology.

The search strategy combined controlled vocabulary with free-text keywords related to depression, exercise, cognition, and neurobiology using Boolean operators. Representative search terms included:

(“major depressive disorder” OR depression) AND (“exercise” OR “physical activity” OR “aerobic exercise” OR “resistance training” OR HIIT) AND (“executive function” OR “working memory” OR “cognitive flexibility” OR inhibition) AND (“BDNF” OR neuroplasticity OR cognition OR neuroinflammation)

The search syntax was adapted to the indexing system of each database while maintaining the same conceptual framework. In addition, the reference lists of eligible systematic reviews and meta-analyses were manually screened to identify relevant studies that were not retrieved through the electronic search.

2.2 Eligibility Criteria

Priority was given to systematic reviews, meta-analyses, randomized controlled trials, and high-quality experimental studies investigating the relationship between exercise and executive functioning in adults diagnosed with MDD. Studies examining the neurobiological effects of exercise in healthy adults were also included when they provided mechanistic insights relevant to cognitive recovery in depression. Publications focusing exclusively on depressive symptom severity without reporting cognitive outcomes were considered only when they contributed important clinical or mechanistic context.

Only peer-reviewed articles published in English were included. Conference abstracts, editorials, opinion papers, and studies lacking sufficient methodological detail were excluded. When multiple publications reported overlapping findings, preference was given to the most comprehensive or methodologically rigorous study.

2.3 Scope of the Review

Unlike previous reviews that have primarily examined the antidepressant effects of exercise, the present review focuses specifically on executive functioning as the principal cognitive outcome. Executive functions—including working memory, inhibitory control, cognitive flexibility, planning, and goal-directed behaviour—were selected because they are consistently associated with functional recovery, occupational performance, and long-term prognosis in individuals recovering from MDD [3,4].

Rather than discussing individual neurobiological mechanisms in isolation, this review integrates clinical and mechanistic evidence to address three fundamental questions:

- Does exercise improve executive functioning during recovery from Major Depressive Disorder?

- Which characteristics of exercise interventions are associated with the greatest improvements in executive functioning?
- Which neurobiological mechanisms most plausibly explain exercise-induced cognitive recovery?

Accordingly, this review adopts a mechanism-oriented perspective that integrates evidence from clinical research, exercise science, and neuroscience into a unified conceptual framework. The overarching objective is not only to determine whether exercise improves executive functioning during recovery from MDD but also to explain how exercise facilitates cognitive rehabilitation and how these findings can be translated into evidence-based exercise prescription.

3. Does Exercise Improve Executive Functions During Recovery from Major Depressive Disorder?

3.1 Current Clinical Evidence

Over the past decade, **accumulating evidence** has identified exercise as one of the most promising non-pharmacological interventions for improving cognitive outcomes in individuals recovering from Major Depressive Disorder (MDD) [11,12]. Although the antidepressant effects of exercise are now well established, increasing attention has shifted toward its potential to restore executive functioning, one of the cognitive domains most consistently impaired in depression [4,11]. Recent systematic reviews and meta-analyses indicate that structured exercise programmes produce measurable improvements in executive functioning, suggesting that exercise contributes not only to symptom reduction but also to cognitive rehabilitation and long-term functional recovery [7,8].

The strongest evidence currently available comes from the systematic review and meta-analysis by **Ren et al.**, which synthesized data from 14 randomized controlled trials involving 1,201 adults with depression [7]. The authors reported a significant overall improvement in global executive functioning following exercise interventions (Hedges' $g = 0.18$), with significant benefits observed for working memory, cognitive flexibility, and reasoning/planning. Subgroup analyses further demonstrated that the largest effects were associated with aerobic exercise performed at moderate-to-vigorous intensity, at least three times per week, with sessions lasting up to 60 minutes and interventions extending for at least 13 weeks. These findings indicate that cognitive improvement depends not only on participation in exercise itself but also on the quality of the exercise prescription, highlighting the importance of optimizing intervention characteristics to maximize cognitive recovery.

Although the reported overall effect size (Hedges' $g = 0.18$) would traditionally be considered small according to conventional interpretations of standardized effect sizes [13], its clinical relevance should not be underestimated. Cognitive deficits in MDD are often persistent, only partially responsive to pharmacological treatment, and strongly associated with impaired psychosocial and occupational functioning [2,4]. Consequently, even modest improvements in executive functioning may translate into meaningful gains in everyday functioning, treatment adherence, workplace performance, and long-term recovery.

Independent findings from the systematic review and meta-analysis by **Contreras-Osorio et al.** support these observations while highlighting important differences among individual executive domains [8]. Their analysis demonstrated significant improvements in working memory, whereas the effects on inhibitory control and cognitive flexibility did not reach statistical significance. Although the limited number of eligible studies and substantial methodological heterogeneity precluded definitive conclusions, these findings suggest that executive functions should not be considered a single, homogeneous construct, as individual domains may differ considerably in their responsiveness to exercise interventions.

More recent evidence further strengthens the role of exercise in cognitive rehabilitation during recovery from MDD [14]. A three-level meta-analysis demonstrated significant improvements in overall executive functioning following aerobic exercise, particularly in inhibitory control and cognitive flexibility, whereas the effect on working memory was smaller and narrowly missed statistical significance. The greatest improvements were observed in programmes performed three times per week, lasting approximately 45 minutes per session, and conducted at moderate-to-vigorous intensity. Together with previous meta-analytic findings, these results reinforce the concept that executive function recovery depends not only on exercise participation but also on optimizing exercise dose and modality. Accordingly, structured exercise should be regarded not merely as an adjunctive treatment for depressive symptoms but as an evidence-informed strategy for cognitive rehabilitation. This perspective further suggests that the characteristics of exercise prescription may determine the magnitude of cognitive improvement, providing a strong rationale for identifying the exercise variables associated with optimal executive function recovery.

Taken together, the available evidence indicates that structured exercise should be regarded as more than an adjunctive treatment for depressive symptoms. Although the effect sizes reported across meta-analyses are generally small to moderate, they are likely to be clinically meaningful given the persistent nature of executive dysfunction in MDD and the limited effectiveness of conventional pharmacological treatments in restoring cognitive functioning. Moreover, the consistency of findings across independent systematic reviews and meta-analyses strengthens confidence in incorporating structured exercise into multidisciplinary rehabilitation programmes aimed at promoting both cognitive and functional recovery [7,8,14]. These observations naturally lead to the next question: **which characteristics of exercise interventions maximize executive function recovery?**

Executive function domain	**Overall evidence**	**Effect of exercise**	**Strength od evidence**
Working memory	Consistent improvement	Small-moderate	High
Cognitive flexibility	Improvement in most high-quality reviews	Small	Moderate-High
Inhibitory control	Promising but less consistent	Small	Moderate
Reasoning/planning	mprovement reported in several RCTs	Moderate	Moderate

Table 1. Summary of the effects of structured exercise on individual domains of executive functioning in adults recovering from Major Depressive Disorder.

4. Which Exercise Characteristics Maximize Executive Function Recovery?

4.1 Exercise Modality

Although the beneficial effects of exercise on executive functioning are increasingly supported by clinical evidence, accumulating findings indicate that not all exercise interventions produce equivalent cognitive outcomes. Differences in exercise modality, intensity, frequency, session duration, and overall programme length appear to influence the magnitude of executive function improvement. Accordingly, identifying the characteristics of the most effective interventions has become a major objective in exercise science and cognitive rehabilitation [7,8].

Among the available training modalities, **aerobic exercise** consistently demonstrates the strongest evidence for improving executive functioning in individuals recovering from Major

Depressive Disorder (MDD). The meta-analysis by **Ren et al.** reported significant improvements in global executive functioning only in interventions primarily based on aerobic exercise, whereas the available evidence for resistance training and mixed exercise programmes remained insufficient to support definitive conclusions [7]. Aerobic interventions were also associated with significant improvements in working memory, cognitive flexibility, and reasoning/planning, suggesting that this modality exerts beneficial effects across multiple executive domains.

More recent findings reinforce these observations. A three-level meta-analysis demonstrated that aerobic exercise significantly improved overall executive functioning, particularly inhibitory control and cognitive flexibility, confirming its position as the intervention currently supported by the most consistent evidence in adults with MDD [14]. Although improvements in working memory were also observed, the pooled effect narrowly failed to reach statistical significance, indicating that individual executive domains may differ in their responsiveness to exercise.

Evidence supporting **resistance training** remains considerably more limited. While resistance exercise has been associated with improvements in depressive symptoms and overall cognitive performance across several clinical populations, relatively few randomized controlled trials have specifically evaluated its effects on executive functioning in individuals with MDD [11]. Consequently, the available evidence remains insufficient to determine whether resistance training provides cognitive benefits comparable to those achieved with aerobic exercise. Rather than indicating a lack of efficacy, this uncertainty primarily reflects the limited number of adequately powered clinical trials.

Similarly, evidence regarding combined aerobic and resistance training remains preliminary. From a physiological perspective, multimodal exercise may theoretically induce complementary adaptations by simultaneously improving cardiovascular fitness, muscular strength, metabolic health, and neuroplasticity. However, the current literature is too heterogeneous to establish whether combined programmes produce greater improvements in executive functioning than aerobic exercise alone. Well-designed randomized controlled trials directly comparing exercise modalities are therefore needed.

Overall, the available evidence supports aerobic exercise as the reference intervention for improving executive functioning during recovery from MDD, whereas the effectiveness of resistance and combined training programmes remains an important area for future investigation.

Nevertheless, exercise prescription should not rely solely on the choice of exercise modality. Contemporary exercise science recognizes that training outcomes result from the interaction of multiple prescription variables rather than exercise type alone. Consequently, optimizing executive function recovery requires consideration of the entire exercise prescription, including **Frequency, Intensity, Time, and Type (FITT)** [15].

4.2 Exercise Dose: Intensity, Frequency, Duration, and Program Length

Beyond exercise modality, **exercise dose** appears to play a critical role in determining cognitive outcomes. Available evidence indicates that executive function recovery is influenced not simply by participation in exercise but by the interaction between exercise intensity, weekly frequency, session duration, and total intervention length [7,14].

From a practical perspective, these findings align closely with the **FITT principle (Frequency, Intensity, Time, and Type)**, which provides a structured framework for designing evidence-based exercise interventions [15]. Rather than prescribing exercise in general terms, clinicians and exercise professionals should optimize each FITT component according to the individual's clinical condition, physical capacity, rehabilitation goals, and functional limitations. Applying this framework is likely to maximize both physiological adaptations and executive function recovery.

Meta-analytic findings consistently support **moderate-to-vigorous intensity** exercise as the most effective intensity for improving executive functioning in adults with depression [7,14]. Interventions performed at this intensity produced significantly greater improvements than low-intensity programmes, suggesting that an adequate physiological stimulus is necessary to induce the neurobiological adaptations underlying cognitive recovery.

Exercise frequency also appears to influence treatment outcomes. Across the available randomized controlled trials, the greatest improvements in executive functioning have generally been observed in programmes involving **three sessions per week** [7,14]. Although higher training frequencies have been investigated less frequently, current findings suggest that three supervised sessions provide an appropriate balance between physiological adaptation, recovery, and long-term adherence.

Likewise, **sessions lasting approximately 45–60 minutes** appear to provide the most consistent cognitive benefits [7,14]. Shorter sessions may provide insufficient physiological stimulation, whereas substantially longer sessions have not consistently demonstrated superior improvements in executive functioning. Although the optimal session duration remains uncertain, the available evidence favors moderate-duration sessions performed consistently over prolonged exercise bouts.

Programme duration represents another important determinant of treatment effectiveness. Interventions lasting **at least 13 weeks** have consistently been associated with larger improvements in executive functioning than shorter programmes [7,14]. This finding supports the hypothesis that sustained exercise exposure is required to induce cumulative neurobiological adaptations—including enhanced neuroplasticity, vascular remodeling, and improved functional brain connectivity—which are unlikely to develop following only brief intervention periods. Collectively, these findings suggest that cognitive rehabilitation should be viewed as a long-term adaptive process rather than an immediate consequence of initiating structured training.

Another important consideration is the principle of **progressive overload**. As cardiorespiratory fitness and exercise tolerance improve throughout rehabilitation, training intensity, duration, or overall volume should be progressively adjusted to maintain an adequate physiological stimulus [15]. Although direct evidence linking progressive overload to executive function recovery in individuals with MDD remains limited, this principle is fundamental to exercise physiology and is likely to facilitate the sustained biological adaptations required for long-term cognitive improvement.

Taken together, these findings indicate that exercise prescription should be regarded as a multidimensional intervention rather than a simple recommendation to increase physical activity. Optimizing exercise modality, intensity, frequency, session duration, and programme length appears essential for maximizing executive function recovery during rehabilitation from MDD.

Equally important is **exercise adherence**, which may substantially influence long-term cognitive outcomes. Even the most effective exercise prescription cannot produce meaningful benefits if participation is inconsistent or prematurely discontinued. Therefore, interventions should be designed not only to maximize physiological adaptations but also to promote long-term adherence through realistic goals, patient education, behavioural support, appropriate supervision, and enjoyable exercise experiences [15].

Finally, exercise prescription should be **individualized**. Factors including age, baseline physical fitness, symptom severity, medication use, psychiatric comorbidities, previous exercise experience, and personal preferences may all influence treatment response. Individualized programmes are more likely to promote adherence and maximize both physiological and cognitive adaptations than standardized protocols. Consequently, future exercise prescriptions for individuals recovering from MDD should combine evidence-based recommendations with patient-specific characteristics to optimize executive function recovery.

Clinical Perspective

The available evidence indicates that the greatest improvements in executive functioning are achieved through **moderate-to-vigorous aerobic exercise performed approximately three times per week**, with sessions lasting **45–60 minutes** over interventions extending for **at least 13 weeks**. However, successful cognitive rehabilitation depends not only on participation in exercise but also on the quality of exercise prescription. Applying the **FITT principle**, incorporating **progressive overload**, promoting **long-term adherence**, and **individualizing exercise programmes** appear to be essential components of interventions designed to maximize executive function recovery.

5. Neurobiological Mechanisms Underlying Exercise-Induced Cognitive Recovery

5.1 Exercise-Induced Neuroplasticity: Is BDNF the Central Mechanism?

Although the beneficial effects of exercise on executive functioning have been consistently demonstrated in clinical studies, the biological mechanisms underlying these improvements remain only partially understood. Among the proposed pathways, **brain-derived neurotrophic factor (BDNF)** has received the greatest scientific attention and is widely regarded as one of the principal mediators of exercise-induced neuroplasticity **[16–18]**.

BDNF is a neurotrophin that plays a fundamental role in neuronal survival, synaptic plasticity, dendritic remodeling, and long-term potentiation—processes that underpin learning, memory, and executive functioning **[16]**. Reduced BDNF concentrations have repeatedly been reported in individuals with Major Depressive Disorder and are associated with impaired hippocampal integrity, disrupted prefrontal cortex function, and poorer cognitive performance **[17]**. Together, these alterations provide a biologically plausible explanation for the executive dysfunction frequently observed during and following depressive episodes.

Both acute and chronic exercise interventions have consistently been shown to increase circulating BDNF concentrations **[16–18]**. Although peripheral BDNF cannot be considered a direct marker of central nervous system activity, accumulating evidence suggests that increases in circulating BDNF reflect broader neuroplastic adaptations that support cognitive recovery. Aerobic exercise appears particularly effective in stimulating BDNF expression, especially when performed at moderate-to-vigorous intensity over several weeks.

Enhanced BDNF availability may facilitate synaptic remodeling within the **prefrontal cortex** and **hippocampus**, brain regions critically involved in working memory, cognitive flexibility, and executive control. Consequently, BDNF currently represents one of the most biologically plausible mechanisms linking structured exercise with improvements in executive functioning. Nevertheless, BDNF alone is unlikely to fully explain exercise-induced cognitive recovery. The relatively modest association between circulating BDNF concentrations and improvements in executive performance suggests that additional biological systems contribute to the observed clinical benefits.

5.2 Neuroinflammation and Immune Modulation

Chronic low-grade inflammation has emerged as one of the most consistently reported biological abnormalities in Major Depressive Disorder **[19]**. Elevated concentrations of pro-inflammatory cytokines—including interleukin-6 (IL-6), tumour necrosis factor-alpha (TNF-α), and C-reactive protein (CRP)—have been associated with impaired neuroplasticity, altered neurotransmitter metabolism, and reduced executive functioning.

Regular exercise exerts well-established anti-inflammatory effects through multiple physiological pathways. Repeated skeletal muscle contractions stimulate the release of anti-inflammatory myokines, improve immune regulation, and attenuate chronic systemic inflammation **[19,20]**. These adaptations may indirectly enhance cognitive performance by restoring a neural environment that is more favourable for synaptic plasticity and efficient neuronal communication.

Importantly, reductions in neuroinflammation are unlikely to act independently. Instead, anti-inflammatory adaptations appear to interact with enhanced neurotrophic signalling, creating conditions that support neuronal plasticity and cognitive recovery. Executive function improvement is therefore likely to reflect the combined effects of enhanced neuroplasticity and reduced inflammatory burden rather than either mechanism in isolation.

5.3 Neurotransmitter Regulation

Executive functioning depends on the coordinated activity of several neurotransmitter systems, particularly **dopamine, serotonin, and norepinephrine [17,21]**. Dysregulation of these systems has been extensively documented in individuals with MDD and is associated with impairments in attention, cognitive flexibility, reward processing, and goal-directed behaviour.

Exercise has been shown to influence both dopaminergic and serotonergic neurotransmission through acute and chronic physiological adaptations. Increased dopamine availability may enhance motivation and cognitive flexibility, whereas improved serotonergic signalling may facilitate emotional regulation and cognitive control. Noradrenergic activation during exercise is also likely to contribute to enhanced attention and information processing.

Despite substantial experimental evidence supporting these mechanisms, direct clinical evidence linking neurotransmitter adaptations with improvements in executive functioning remains limited. Accordingly, neurotransmitter regulation should be viewed as one component of a broader network of interacting biological adaptations rather than as an isolated explanatory mechanism.

5.4 Cerebral Blood Flow and Functional Brain Connectivity

Exercise also induces cardiovascular adaptations that extend to the central nervous system. Regular aerobic training improves endothelial function, increases cerebral perfusion, and enhances vascular responsiveness, thereby facilitating oxygen and nutrient delivery to metabolically active brain regions **[21]**.

Neuroimaging studies further indicate that exercise promotes functional reorganization within large-scale brain networks, including the **frontoparietal network**, **default mode network**, and **salience network [21,22]**. Because executive functions depend on efficient communication among distributed cortical regions, improvements in functional connectivity may represent another key mechanism underlying cognitive recovery.

Enhanced cerebral perfusion together with more efficient large-scale brain network organization may facilitate greater recruitment of prefrontal cortical regions during executive tasks, thereby contributing to improvements in working memory, inhibitory control, and cognitive flexibility.

5.5 Mitochondrial Function and Brain Energy Metabolism

Efficient executive functioning requires substantial metabolic support. Mitochondrial dysfunction has increasingly been implicated in the pathophysiology of depression, contributing to impaired neuronal energy production, oxidative stress, and reduced synaptic efficiency **[22]**.

Exercise stimulates mitochondrial biogenesis, improves oxidative phosphorylation, and enhances cellular energy metabolism throughout the body, including the brain **[22]**. These adaptations increase neuronal resilience and may support sustained cognitive performance during demanding executive tasks.

Although direct evidence in individuals recovering from MDD remains limited, accumulating experimental findings indicate that improved mitochondrial function complements neuroplastic and cerebrovascular adaptations, thereby contributing to exercise-induced cognitive recovery.

5.6 An Integrated Neurobiological Model

Taken individually, none of the proposed mechanisms fully explains the improvements in executive functioning observed following structured exercise interventions. Rather, the available evidence supports the view that exercise induces a coordinated cascade of biological adaptations involving neuroplasticity, immune regulation, neurotransmitter modulation, cerebrovascular remodeling, mitochondrial function, and large-scale brain network reorganization **[16–23]**.

This integrated perspective provides the most plausible explanation for why structured exercise consistently improves executive functioning despite relatively modest changes observed within individual biological pathways. Executive function recovery is therefore unlikely to result from a single molecular mechanism; instead, it appears to emerge from the coordinated interaction of multiple physiological systems that collectively enhance brain function during recovery from Major Depressive Disorder.

Clinical Perspective

Current evidence suggests that exercise-induced improvements in executive functioning are best explained by an **integrated neurobiological model** rather than a single biological pathway. Although **BDNF-mediated neuroplasticity** currently has the strongest empirical support, optimal cognitive recovery is likely to depend on the coordinated interaction of enhanced neuroplasticity, reduced neuroinflammation, improved neurotransmitter regulation, increased cerebral perfusion, mitochondrial adaptations, and large-scale functional brain network reorganization.

6. Integrated Mechanistic Model

The evidence synthesized in this review suggests that no single biological mechanism fully explains the beneficial effects of exercise on executive functioning during recovery from Major Depressive Disorder (MDD). Although numerous studies have demonstrated exercise-induced increases in brain-derived neurotrophic factor (BDNF), reductions in systemic inflammation, improvements in neurotransmitter regulation, enhanced cerebral perfusion, and favorable changes in mitochondrial function, each mechanism alone accounts for only part of the observed cognitive improvement [7,16–21]. Based on the available evidence, we propose an **Integrated Exercise–Neurobiology Model of Executive Function Recovery**, in which exercise-induced cognitive improvement emerges from coordinated adaptations occurring across multiple physiological systems rather than from a single molecular pathway.

From this perspective, exercise should be regarded as a **multimodal biological stimulus** capable of simultaneously influencing peripheral physiology and central nervous system function. Acute exercise initiates a cascade of physiological responses, including increased cardiovascular activity, skeletal muscle contraction, endocrine signaling, immune modulation, and transient metabolic stress. Repeated exposure to these stimuli induces long-term adaptations involving neuroplasticity, vascular remodeling, mitochondrial biogenesis, improved metabolic regulation, and functional reorganization of large-scale brain networks [16–22]. Within the proposed model, peripheral physiological adaptations represent the initiating biological stimulus, whereas central neurobiological adaptations constitute the proximal mechanisms directly supporting executive function recovery. Together, these coordinated adaptations create a neural environment that promotes more efficient executive processing.

A central feature of the proposed model is the interaction between peripheral and central adaptations. Exercise-induced myokines, neurotrophic factors, metabolic regulators, and inflammatory mediators generated outside the brain may influence neural plasticity through complex signaling pathways [18,20,23]. Simultaneously, improvements in cardiovascular fitness increase cerebral blood flow and oxygen delivery, thereby enhancing the metabolic capacity of cortical regions responsible for executive control [17,21]. Rather than operating independently, these mechanisms appear to reinforce one another, producing cumulative biological effects that exceed the contribution of any individual pathway.

The **prefrontal cortex** represents the principal neural target within this framework. Executive functions—including working memory, inhibitory control, cognitive flexibility, planning, and decision-making—depend on efficient communication between the prefrontal cortex and distributed cortical and subcortical brain networks [3,4]. Exercise-induced improvements in functional connectivity, together with enhanced synaptic plasticity and reduced neuroinflammatory burden, may increase the efficiency of these networks, thereby facilitating the higher-order cognitive processes required for adaptive behaviour [16,19,21].

The proposed model is also unlikely to operate in a strictly linear manner. Improvements in executive functioning may themselves facilitate greater engagement in regular physical activity by enhancing self-regulation, planning, motivation, and behavioural control. Sustained participation in exercise may subsequently reinforce long-term adherence, generating a **positive feedback loop** that further amplifies physiological and neurobiological adaptations over time. This reciprocal relationship may help explain why continued exercise participation is frequently associated with progressively greater cognitive and functional benefits. Nevertheless, this positive feedback mechanism remains conceptual and has yet to be directly confirmed in longitudinal intervention studies.

The present framework also offers a plausible explanation for why **exercise prescription** influences cognitive outcomes. Aerobic exercise performed at moderate-to-vigorous intensity for a sufficient duration appears to provide the strongest and most consistent physiological stimulus for inducing coordinated neurobiological adaptations [7,14]. In contrast, programmes characterized by insufficient intensity, frequency, or duration may fail to generate the cumulative biological changes required to produce clinically meaningful improvements in executive functioning. Consequently, cognitive recovery may depend not only on whether individuals engage in exercise but also on the quality of the exercise prescription itself.

The proposed model further suggests that improvements in executive functioning may mediate broader clinical outcomes during recovery from MDD. Enhanced executive control may facilitate treatment adherence, strengthen emotional regulation and self-management behaviours, improve occupational functioning, promote successful social reintegration, and ultimately enhance quality of life while potentially reducing the risk of depressive relapse [2,4,5]. Within this framework, executive function recovery represents an intermediate therapeutic target linking structured exercise with long-term functional recovery.

Although this conceptual framework integrates current evidence from neuroscience, psychiatry, and exercise physiology, several important questions remain unresolved. Direct causal relationships between individual biological adaptations and improvements in executive functioning have not yet been conclusively established. Moreover, relatively few longitudinal studies have simultaneously evaluated exercise characteristics, biological markers, neuroimaging outcomes, and executive performance within the same cohort. Future research employing multimodal experimental designs will therefore be essential to validate, refine, and experimentally test the proposed model.

Overall, the **Integrated Exercise–Neurobiology Model** proposed in this review provides a biologically plausible framework linking exercise prescription with coordinated physiological and neurobiological adaptations, executive function recovery, and long-term functional outcomes. Rather than targeting a single pathological process, structured exercise appears to induce multiple interacting biological adaptations that collectively facilitate cognitive rehabilitation following Major Depressive Disorder. Although several components of the model require further experimental validation, the framework offers a foundation for future mechanistic research and may support the development of increasingly precise, evidence-based exercise interventions aimed at maximizing cognitive recovery in individuals with MDD.

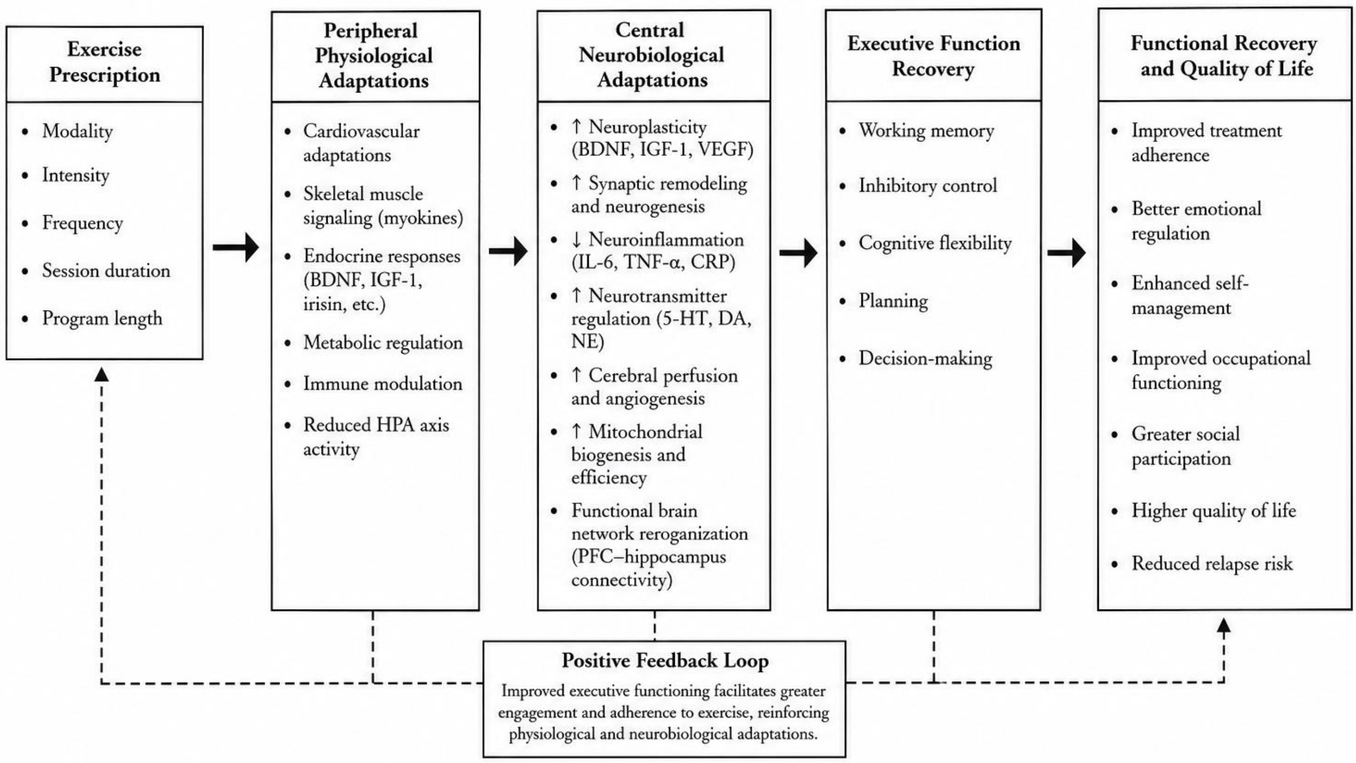

Figure 1. Integrated Exercise–Neurobiology Model of Executive Function Recovery. Structured exercise induces peripheral physiological adaptations, which drive central neurobiological changes, leading to improvements in executive functioning and broader functional outcomes. Enhanced cognition further promotes long-term exercise adherence, creating a positive feedback loop.

Proposed Conceptual Framework

Clinical Perspective

Exercise-induced recovery of executive functioning is most plausibly explained by the coordinated interaction of multiple physiological and neurobiological systems rather than by a single biological mechanism. The **Integrated Exercise–Neurobiology Model** proposed in this review provides a conceptual framework linking exercise prescription with peripheral and central adaptations, executive function recovery, and long-term functional outcomes. This model may also serve as a foundation for future mechanistic studies and for developing evidence-based exercise interventions aimed at maximizing cognitive rehabilitation in individuals recovering from Major Depressive Disorder.

7. Practical Implications for Exercise Professionals

The findings presented in this review have important implications for professionals involved in exercise prescription and rehabilitation. While exercise has long been recognized as an effective adjunctive treatment for reducing depressive symptoms, the available evidence indicates that its therapeutic role extends well beyond mood improvement. Exercise professionals should therefore regard structured physical activity not only as a strategy for improving mental health but also as a clinically meaningful intervention capable of supporting executive function recovery during rehabilitation from Major Depressive Disorder (MDD).

A key practical implication is that **cognitive recovery should be recognized as a primary rehabilitation outcome**, alongside improvements in depressive symptoms. Restoration of executive functioning—including working memory, inhibitory control, cognitive flexibility, planning, and decision-making—may contribute directly to improved treatment adherence, enhanced emotional self-regulation, greater occupational performance, and increased independence in everyday life. Consequently, exercise interventions should be designed to facilitate both psychological and cognitive recovery rather than focusing exclusively on symptom reduction.

Based on the current evidence, **moderate-to-vigorous aerobic exercise** should be considered the preferred exercise modality when the primary therapeutic objective is to improve executive functioning. Programmes performed approximately **three times per week**, with **45–60-minute sessions** over a minimum duration of **13 weeks**, currently represent the exercise prescription supported by the strongest evidence. Although resistance training and combined exercise interventions appear promising, additional high-quality randomized controlled trials are required before comparable recommendations can be made.

From a practical perspective, exercise prescription should follow established principles of exercise science, including the **FITT principle**, **progressive overload**, and **individualization**. Exercise frequency, intensity, duration, and modality should be adjusted according to each patient's clinical presentation, baseline physical fitness, rehabilitation goals, and response to training. As exercise tolerance improves, training load should be progressively increased to maintain an adequate physiological stimulus while minimizing excessive fatigue and reducing the risk of treatment discontinuation.

Long-term **exercise adherence** should be regarded as a therapeutic objective rather than simply a measure of patient compliance. Even the most effective exercise prescription cannot improve cognitive outcomes if participation is inconsistent or prematurely discontinued. Accordingly, exercise professionals should incorporate behavioural strategies that promote sustained engagement, including realistic goal setting, patient education, individualized progression, regular feedback, supervised training when appropriate, and activities that align with patients' preferences and enjoyment.

The findings of this review also support a **multidisciplinary approach** to rehabilitation. Exercise professionals should collaborate closely with psychiatrists, psychologists, physiotherapists, primary care physicians, and other healthcare providers to integrate structured exercise safely into comprehensive treatment plans. Such collaboration facilitates individualized progression, improves patient safety, and increases the likelihood of long-term functional recovery. Rather than replacing pharmacological or psychological treatment, structured exercise should be considered an evidence-informed complementary intervention capable of addressing cognitive deficits that frequently persist despite conventional therapy.

Evaluation of treatment outcomes should extend beyond changes in depressive symptom severity. Whenever feasible, clinicians and researchers should include standardized assessments of executive functioning, cardiorespiratory fitness, functional capacity, exercise adherence, and health-related quality of life. A multidimensional evaluation strategy provides a more comprehensive assessment of treatment effectiveness while facilitating the identification of exercise prescriptions that maximize cognitive recovery.

Finally, the findings presented in this review emphasize the importance of translating advances in exercise physiology and neuroscience into clinical practice. Future intervention studies should systematically investigate how specific components of exercise prescription—including modality, intensity, frequency, progression, and programme duration—influence both neurobiological adaptations and executive function outcomes. Such evidence will facilitate the development of increasingly precise, **mechanism-based exercise prescriptions** capable of optimizing cognitive rehabilitation in individuals recovering from MDD.

Practical Recommendations

Based on the available evidence, the following recommendations may assist exercise professionals working with individuals recovering from Major Depressive Disorder:

- Recognize executive function recovery as a therapeutic objective alongside improvement in depressive symptoms.
- Prioritize **moderate-to-vigorous aerobic exercise** as the intervention currently supported by the strongest clinical evidence.
- Apply the **FITT principle** and progressively adjust training load according to individual patient response.
- Prescribe exercise approximately **three times per week**, with **45–60-minute sessions** over programmes lasting **at least 13 weeks**, while adapting these parameters to individual clinical circumstances.
- Individualize exercise prescription according to baseline physical fitness, symptom severity, medication use, psychiatric comorbidities, previous exercise experience, and patient preferences.
- Promote long-term exercise adherence through behavioural support, realistic goal setting, supervision when appropriate, and enjoyable exercise experiences.
- Collaborate within multidisciplinary healthcare teams to integrate structured exercise safely into comprehensive rehabilitation programmes.
- Monitor cognitive, physical, and functional outcomes rather than relying exclusively on changes in depressive symptom severity.
- Encourage lifelong participation in regular physical activity, as sustained exercise appears necessary to maintain the neurobiological adaptations associated with cognitive recovery.

Clinical Perspective

Exercise professionals should regard structured exercise as a **mechanism-based therapeutic intervention** rather than solely as a strategy for reducing depressive symptoms. The available evidence supports individualized **moderate-to-vigorous aerobic exercise**, prescribed according to established principles of exercise science, as a clinically meaningful approach to promoting executive function recovery and facilitating long-term functional rehabilitation in individuals recovering from Major Depressive Disorder.

8. Limitations

Several limitations should be considered when interpreting the findings presented in this narrative review. First, the conclusions are based on studies that differ substantially in participant characteristics, exercise interventions, outcome measures, and methodological quality. Considerable heterogeneity exists across the available literature with respect to exercise modality, intensity, frequency, programme duration, supervision, and adherence, making direct comparisons challenging and limiting the ability to identify a universally optimal exercise prescription [7,8,14].

Second, executive functioning has not been assessed consistently across clinical trials. A wide variety of neuropsychological tests have been used to evaluate distinct components of executive functioning, potentially obscuring meaningful differences in the responsiveness of individual domains, including working memory, inhibitory control, cognitive flexibility, planning, and decision-making. Greater standardization of cognitive outcome measures would substantially improve comparability across future investigations [4,5,8].

Third, although current evidence supports the beneficial effects of exercise on executive functioning, relatively few randomized controlled trials have been specifically designed with cognitive outcomes as their primary endpoint. In many intervention studies, executive function measures represent secondary outcomes, potentially limiting statistical power and increasing the risk of Type II error. Moreover, most available trials include relatively modest sample sizes, which may reduce the precision of treatment effect estimates [7,8].

Another important limitation concerns the interpretation of the proposed neurobiological mechanisms. Much of the mechanistic evidence has been derived from experimental studies, neuroimaging investigations, or research conducted in healthy populations rather than individuals recovering from Major Depressive Disorder [16–23]. Consequently, direct causal relationships between exercise-induced biological adaptations and improvements in executive functioning have not yet been conclusively established. Accordingly, the **Integrated Exercise–Neurobiology Model** proposed in this review should be regarded as a biologically plausible conceptual framework rather than definitive evidence of causal mechanisms.

The narrative design of the present review also represents an inherent limitation. Unlike systematic reviews and meta-analyses, narrative reviews do not follow predefined protocols for study selection or formal risk-of-bias assessment and are therefore more susceptible to selection and publication bias [10]. Nevertheless, this methodological approach was intentionally chosen because the primary objective of the present review extended beyond summarizing the available evidence. Specifically, it sought to integrate findings from exercise physiology, neuroscience, and psychiatry into a unified conceptual framework—an objective that would have been considerably more difficult within the methodological constraints of a conventional systematic review.

Finally, cognitive recovery following Major Depressive Disorder is likely influenced by numerous factors beyond exercise itself. Medication use, psychiatric comorbidities, baseline physical fitness, genetic variability, sleep quality, nutritional status, psychosocial support, and individual differences in exercise adherence may all modify the cognitive response to exercise interventions. Furthermore, reverse causality cannot be completely excluded, as individuals with better preserved executive functioning may also be more likely to engage consistently in structured exercise programmes. Future longitudinal and mechanistic studies should therefore examine these interacting factors simultaneously to better understand the determinants of cognitive recovery.

Despite these limitations, the consistency of findings across multiple independent systematic reviews and meta-analyses provides growing confidence that structured exercise contributes meaningfully to executive function recovery following Major Depressive Disorder [7,8,14]. Accordingly, the **Integrated Exercise–Neurobiology Model** proposed in this review should be regarded as a hypothesis-generating framework that synthesizes the current evidence while providing a foundation for future mechanistic and clinical research.

Clinical Perspective

Although important methodological limitations and knowledge gaps remain, the available evidence consistently supports a beneficial role of structured exercise in executive function recovery following Major Depressive Disorder. The **Integrated Exercise–Neurobiology Model** proposed in this review should therefore be interpreted as a biologically plausible framework that integrates current evidence, guides future mechanistic investigations, and supports the development of increasingly precise, evidence-based exercise interventions for cognitive rehabilitation.

9. Future Directions

Although substantial progress has been made in understanding the relationship between exercise and cognitive recovery in Major Depressive Disorder (MDD), several important questions remain unanswered. Future research should move beyond establishing whether exercise improves executive functioning and instead focus on identifying the specific exercise prescriptions and biological mechanisms that optimize cognitive recovery.

One of the highest priorities is the development of well-designed randomized controlled trials in which executive functioning is defined as a **primary outcome** rather than a secondary endpoint. Future studies should employ standardized neuropsychological assessment batteries to improve comparability across investigations and enable more precise evaluation of individual executive domains, including working memory, inhibitory control, cognitive flexibility, planning, and decision-making [4,5,7,8].

Direct comparisons between different exercise modalities also remain limited. Although current evidence provides the strongest support for aerobic exercise, relatively few studies have directly compared aerobic exercise, resistance training, high-intensity interval training (HIIT), combined exercise, and mind-body interventions within the same clinical population [7,8,14]. Such comparative trials are essential to determine whether specific exercise modalities preferentially improve particular executive functions or induce distinct neurobiological adaptations.

Future investigations should also establish **dose–response relationships** by systematically manipulating exercise intensity, frequency, session duration, and intervention length. Identifying the minimum effective dose and the optimal combination of training variables would facilitate the development of evidence-based exercise prescriptions specifically designed to maximize cognitive rehabilitation rather than general improvements in physical or mental health [7,14,15].

Another important priority is the integration of **multimodal outcome measures** within a single experimental design. Combining neuropsychological assessment with neuroimaging, circulating biomarkers, physiological measurements, and assessments of physical fitness would provide a more comprehensive understanding of how peripheral biological adaptations translate into changes in brain function and executive performance. Such multidimensional approaches may help clarify the causal pathways underlying exercise-induced cognitive recovery [16–23].

Greater attention should also be directed toward **individual variability** in treatment response. Factors including age, biological sex, baseline cognitive impairment, cardiorespiratory fitness, medication use, psychiatric comorbidities, sleep quality, and genetic characteristics may influence both neurobiological adaptations and clinical outcomes [24,25]. Future research should therefore adopt principles of **precision medicine** to identify which patients are most likely to benefit from specific exercise interventions.

Long-term follow-up studies represent another important research priority. Most intervention trials evaluate outcomes immediately after programme completion, providing limited information regarding the durability of cognitive improvements [7,8]. Future longitudinal studies should determine whether continued participation in exercise is necessary to maintain executive function gains and whether sustained cognitive improvements contribute to reduced relapse rates and improved long-term functional recovery.

Finally, future research should place greater emphasis on translating mechanistic discoveries into clinical practice. Rather than investigating isolated biological pathways, studies should examine how multiple physiological systems interact to influence executive functioning and determine whether exercise prescriptions can be optimized according to specific neurobiological profiles. Such an approach may facilitate the development of **mechanism-based, personalized exercise interventions** capable of maximizing cognitive rehabilitation in individuals recovering from MDD.

Clinical Perspective

Future research should prioritize optimizing exercise prescription, identifying causal neurobiological mechanisms, and developing personalized exercise interventions that maximize executive function recovery. Integrating randomized clinical trials with multimodal biological and physiological assessments will be essential for translating current evidence into **precision exercise medicine** for individuals recovering from Major Depressive Disorder.

10. Conclusions

Executive dysfunction represents one of the most persistent and clinically relevant consequences of Major Depressive Disorder (MDD), frequently limiting functional recovery despite successful remission of depressive symptoms [4,5]. Restoring executive functioning has therefore emerged as an important therapeutic objective that extends beyond the traditional focus on symptom reduction alone.

The evidence synthesized in this review demonstrates that structured exercise is a clinically meaningful intervention for improving executive functioning during recovery from MDD. Across the available literature, the greatest benefits have consistently been observed following moderate-to-vigorous aerobic exercise performed regularly over a sufficient duration [7,8,14]. These findings indicate that exercise should no longer be regarded simply as a complementary treatment for depression but as an evidence-informed strategy capable of supporting cognitive rehabilitation.

Current evidence further suggests that the magnitude of cognitive recovery depends not only on participation in exercise but also on the characteristics of the exercise intervention itself. Exercise modality, intensity, frequency, session duration, and overall programme length all appear to influence the neurobiological adaptations associated with executive function recovery [7,14,15]. Consequently, optimizing exercise prescription may be as important as promoting exercise participation.

The biological mechanisms underlying these cognitive improvements are complex and multifactorial. Rather than supporting a single explanatory pathway, the available evidence indicates that structured exercise induces coordinated adaptations involving neuroplasticity, neuroinflammation, neurotransmitter regulation, cerebral perfusion, mitochondrial function, and large-scale functional brain network reorganization [16–23]. The Integrated Exercise–Neurobiology Model proposed in this review provides a conceptual framework linking these interacting biological adaptations with improvements in executive functioning and subsequent functional recovery.

From a clinical perspective, these findings support the integration of structured exercise into multidisciplinary rehabilitation programmes for individuals recovering from MDD. Exercise professionals, physiotherapists, psychiatrists, psychologists, and other healthcare providers should recognize executive function recovery as an important therapeutic target and incorporate evidence-informed exercise prescription into comprehensive patient care.

Despite encouraging findings, several important questions remain unresolved. Future research should prioritize high-quality randomized controlled trials designed specifically to investigate executive functioning as a primary outcome, identify optimal exercise prescriptions, and clarify the causal biological pathways responsible for cognitive recovery. Such evidence will be essential for developing personalized exercise interventions capable of maximizing long-term cognitive and functional outcomes.

In conclusion, the available evidence supports a fundamental shift in how exercise is viewed within the rehabilitation of Major Depressive Disorder. Rather than serving solely as an adjunctive intervention for alleviating depressive symptoms, structured exercise should be recognized as a mechanism-based therapeutic strategy capable of promoting executive function recovery through coordinated physiological and neurobiological adaptations. Continued advances in mechanistic research, combined with increasingly precise exercise prescription, have the potential to transform cognitive rehabilitation by enabling personalized, evidence-based interventions that optimize long-term functional recovery and contribute to the emerging field of precision exercise medicine. **These conclusions are further reinforced by recent high-quality evidence demonstrating that appropriately prescribed exercise should be considered an integral component of comprehensive depression management and an important direction for future precision rehabilitation strategies [24,25].**

Disclosure

The authors declare no conflict of interest.

Author Contributions

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Methodology: AT, AZ,

Formal analysis: AT, AZ, MŁ

Investigation: AT, AGS, HL

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Writing – review & editing: AZ, AT, GS, AM, AGS, HL, AZY, MŁ

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