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Physical activity as a factor influencing mental health: integrating neurobiological mechanisms, regulatory processes, and the sports context

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Abstract

Physical activity (PA) is a recognized protective factor for mental health; however, its mechanisms of action and the variability of its therapeutic effects remain the subject of active research. This paper is a narrative review of the literature aimed at synthesizing available data on the neurobiological and behavioral mechanisms of PA, along with an analysis of environmental factors that modulate its effectiveness, with a particular focus on the context of competitive sports.

Physical activity influences mental health through three main mechanisms: neuroplasticity based on the stimulation of neurotrophic factors, the regulation of metabolic and inflammatory processes, and the improvement of executive function and cognitive control. These effects are simultaneously significantly modulated by systemic factors, such as sleep quality, the severity of psychosocial stress, and the interpersonal environment.

Based on our analysis, we identify three trajectories of response to physical activity and propose a three-level integrative model encompassing biological, psychological, and environmental dimensions. An analysis of competitive sports as a boundary model reveals the limitations of a simplified understanding of the relationship between the amount of physical activity and mental well-being and highlights the need to consider contextual factors when designing therapeutic interventions.

Keywords: physical activity; mental health; neuroplasticity; emotion regulation; competitive sports; response heterogeneity; integrative model

1. Introduction

Many experimental and epidemiological studies have found a relationship between physical activity and mental health. [1,4,5,7,22] High physical activity is related to good mental health and a reduced risk of anxiety and depression. [4,5,7,20,21,28,29,31] Physical activity resulted in 43% fewer mental poor health days on average in physically active versus sedentary subjects when investigating over 1.2 million U.S residents with a cross-sectional study design, the best outcome was in a physical activity intervention group doing 45 minutes three times weekly. [4]

Intervention studies however are more complex to interpret.[7] Effect is also highly variable between individuals, does not appear to be maintained without continued practice, and is strongly modulated by other (biological, psychological, environmental) variables.[5,8] AF is probably therefore best conceptualized not as an intervention that works for all and everyone but as one factor within a complex control system which only works in certain contexts. [1,7,30]

2. The mechanisms underlying physical activity

2.1 Neuroplasticity and neural adaptation

Physical activity triggers the production of some important neurotrophic factors - BDNF, VEGF and IGF-1.[6] The factors support the neurogenesis, synaptogenesis and angiogenesis processes in the CNS and this effect is especially clear in the regions responsible for mental functioning - the hippocampus, performing memory and emotion regulation functions, the prefrontal cortex, taking responsibility of cognitive control functions, and subcortical regions composing the reward system.[7] Neuroplasticity is, however, required, but not sufficient for increased mental functioning – adaptation is shaped mainly by the circumstances of its realization.[25]

Table 1. Mechanisms through which physical activity affects mental health

Level	Mechanism	Description	Clinical impact
Neurobiological	Neuroplasticity	BDNF, VEGF, IGF-1; neurogenesis in the hippocampus	Improved emotional regulation, reduced symptoms of depression and anxiety
Neurobiological	Metabolism and Inflammation	Modulation of the kynurenine pathway, reduction of pro-inflammatory cytokines	Restoring the CNS's adaptability, improving mood
Cognitive-behavioral	Executive functions	Activation of the prefrontal cortex, improved cognitive control	Better impulse control, reduced rumination
Behavioral	Emotional Regulation	Teaching the modulation of emotional and cognitive responses	Mental resilience, improved stress tolerance
System-wide	Sleep	The two-way relationship between sleep and mood	Regulation of the circadian rhythm, improved recovery
System-wide	Environment	Pressure, interpersonal relationships, psychosocial context	Modulation or neutralization of biological effects

2.2 Metabolism, inflammation, and systemic mechanisms

Beyond its specific effect on the neuroplasticity of certain brain regions, PA affects psychological status through other systemic mechanisms. The consistent physical exercise corrects the functioning of the brain metabolism, regulates the activities of the kynurenine pathway and alleviates systemic chronic

inflammation which is an important pathogenic component of the disease-related symptoms in anxiety and depressive disorders.[26,27] However it should be emphasized, the enhancement of the inflammation might negatively impact the effect of the PA on neuroplasticity which is supposed to be attenuated by the inflammation at the same time. From this viewpoint PA attenuates the illness not through the specific symptomatic improvement but through reestablishment of plasticity in nervous system.

2.3 Cognitive-behavioral mechanisms

Physical activity also has a positive impact on the higher cognitive functions:executive functions, cognitive controlandaffect regulation(cognitive-behavioral level). It should be pointed out that when depressive symptoms decreased, cognitive control significantly increased, indicating a reciprocal relationship and synergy between the biological and psychological mechanisms and not just independent influences of the two. From this perspective,PAcan be considered as a special kind of regulation training. That is, one could gradually gain the control over his/her emotional and cognitive reactions in the face of the stress situation.[21]

Though the biological and psychological mechanisms as described above seemed consistent, results of intervention studies demonstrated large differences in how much individuals react to the PA intervention-which should be analyzed separately.[8]

3. Heterogeneity of effects: a comparative analysis

Three response pathways are apparent from the existing empirical evidence. This first pathway-the improvement of consistency-is characterized by an unchanging high level of activity during the study and approaching the 150 minutes/day in a stable psychosocial environment.[20] This second pathway is a transient response where individuals improve during the intervention and lose the benefits when it terminates (so the stability of activity becomes clear). The third pathway-the improvement of limited scope-is variable from person to person and depends on age, pre-existent abilities and clinical status.[26] This implies that an interaction between biology and environment determines the response to AF and it is not just dependent on parameters of training. The pathways defined here are not clinical groups but analytical constructs obtained after examination of all available studies, clinical trials and observation studies in order to explain this variability of effects.

4. Competitive sports as a boundary model

4.1 High activity and a high prevalence of disorders

In fact, our data indeed indicates the highest prevalence of depression, anxiety, and sleep disorders in elite athletes, whereas they engage objectively highest amount of physical activity.[9,11] Specificity of the sport context (strong competition, performance pressure, over-training, lack of autonomy) causes a chronic stress condition which counteracts with the possible protective activity benefit.[9,10,11,14,19,23,24,25] Chronic performance-related stress may initiate a self-perpetuating cycle involving sleep disturbance, impaired recovery, overtraining, and increased vulnerability to anxiety and depressive symptoms.[12,13]

Table 2. The Paradox of Competitive Sports

Variable	Expectations	Reality
Physical activity	Better mental health care	Higher prevalence of depression and anxiety disorders
Sleep	Better recovery and sleep quality	Circadian rhythm disorders, insomnia
The sports community	Supportive, motivating	Chronic stress, pressure to perform, low autonomy
Coach	The athlete's mental stability	He himself is at risk of burnout and mental health issues

4.2 Sleep as a key mediator

Sleep is also one of the mediators between exercise and mental health and it is highly important in sport in general and competition in particular. It has been reported that sleep disorders such as low sleep duration, low sleep quality and disruption of circadian rhythm because of the training and competition schedules are very prevalent in elite athletes and significantly more common compared to non-athletes.[3,18] However, this connection is likely to be bidirectional, meaning that sleep disorders lead to increased susceptibility to depression and anxiety disorders which in their turn increase the problem

with sleep.[27] One thing to add is that by reducing restorative and adaptive processes sleep deprivation weakens the protective potential of physical activity itself.

4.3 The role of coaches as part of the system

Another important but distinct and interconnected aspect of the sports context is the role of the coach. Available data show that coach elite is a subpopulation at higher risk of developing a psychiatric disorder; it reports symptoms of depression, anxiety and burnout due to particular job conditions (high responsibility, lack of job security and constant need to perform).[15,16] At the same time, the coach is the primary modifier of the athlete psychosocial environment-quality of coach-athlete relationship, communication and teamwork climate can promote or reduce the positive effects on athletes by physical activity. Coach health is not isolated but it's a systemic variable.

5. The integrative model

Based on the presented analysis, we propose a three-level integrative model that helps explain the heterogeneity of the effects of physical activity on mental health. The biological level encompasses processes of neuroplasticity, brain metabolism, and inflammation regulation—constituting the neurobiological basis of adaptation. The psychological level refers to emotional regulation and cognitive control, which determine an individual's ability to benefit from biological effects. The environmental level—encompassing sleep quality, stress levels, and interpersonal relationships—acts as a context that modulates the effectiveness of the other two levels.

A key feature of the model is the assumption that the therapeutic efficacy of AF depends on the synchronization of all three levels. A discrepancy between them—as in the case of an athlete with optimal biological activity functioning in a destructive psychosocial environment—leads to a weakening or elimination of the protective effects. This model explains both cases of full therapeutic response and the trajectories of limited effectiveness described in Section 3.

Table 3. Factors influencing the effectiveness of physical activity — a three-level model

Level	Factors	Clinical example
Biological	Inflammation, brain metabolism, neuroplasticity	Depression with elevated CRP — reduced response to AF; BDNF deficiency as a marker of poor adaptation
Psychological	Cognitive functions, emotional regulation, cognitive control	Executive function deficits that limit adherence to an exercise program
Environmental	Sleep quality, stress levels, interpersonal relationships	An athlete with sleep disorders and high blood pressure — no protective effect despite high activity levels

6. Conclusions

Regarding mental health, physical activity has been revealed to possess quite therapeutic potential but its effect is undoubtedly shaped by biological, psychological and environmental influences.[1,4,5,7,21,29,31] Neuroplasticity is the key component for the influence of exercise on mental health but it is shaped by systematic factors; in this context, inflammation, quality of sleep and psychosocial stress levels. Moreover the permanence of observed benefits depends to a great extent on the adherence to the regular activity and the maintenance of stable conditions of the environment in which this activity is performed.

By considering the applied setting of competitive sport, there are obvious shortcomings in simple models that suggest that physical activity level is monotonically related to psychological health. Within competitive sport, it is obvious that sleep quality, chronic stress, and quality of interpersonal relationships ought to be part of an exercise prescription designed intervention.[14] In light of the results above, the research need for an individually tailored approach which considers the subject's unique biological and environmental characteristics continues to be high.

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