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Effects of physical exercise on children with attention deficit hyperactivity disorder

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ABSTRACT

Attention deficit hyperactivity disorder (ADHD) is one of the most commonly neurodevelopmental disorders with a complex symptomatology in children, and frequently suffer from deficits in executive functions and motor abilities. Although medication-based treatments usually have a positive effect, possible side effects may result in a need for an adjunctive intervention. Present studies show positive effect of physical exercise on cognitive function. Therefore, the purpose of the current study is to thoroughly examine the effects of physical exercise in children with ADHD. Preliminary evidence shows both acute and chronic physical exercise are beneficial to ADHD symptoms, executive function, and motor abilities. Benefits of acute exercise may gradually accumulate over time. Such benefits reflect the positive correlation between cognition and physical activity, and these benefits will also lead to changes in executive function after long-term training. Aerobic could induce to increase the neurotransmitter ie. serotonin, dopamine, brain-derived neurotrophic factor (BDNF) and brain blood flow. Perceptual motor and meditation could lead to neuroplasticity in nerve cells and synaptic connections; furthermore, strengthening the sensory-motor base contributes to the improvement of attention. An exercise program for children with ADHD include to moderate to high intensity interval training and cognitive tasks are suitable. The preliminary state of the evidence supports physical exercise as an adjunctive treatment for ADHD at this time.

Attention deficit hyperactivity disorder (ADHD) is one of the most common neurodevelopmental disorders seen in the early childhood [1]. The global prevalence of the ADHD is 5.29%–7.2%, which is increasing in recent years [2]. Besides

the typical symptoms of this disorder include inattention, hyperactivity, and impulsivity [3], it was found that children with ADHD often suffer from other comorbidities, of which the proportions of patients with ADHD combined with

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oppositional defiant disorder [4], conduct disorder, depression, anxiety [5] and Tourette syndrome [6] are relatively high. These children or adolescents with ADHD have impulsive behavior, reduced information-processing capacity, or inability to pay attention in class. Therefore, they are unable to complete the homework assigned by their teachers in a timely manner, which may affect their academic achievement [7]. Limited motor coordination, poor emotional regulation, low frustration tolerance, and low sleep quality causes them to encounter more difficulties in academic and interpersonal relationships than normal children [8]. Furthermore, they may feel excluded as their peers do not interact with them, thereby developing social maladjustment and low self-confidence [9].

Currently, treatment methods for ADHD mostly involve medications, psychological counseling, and behavioral therapy. Recent many studies found that the appropriate exercise training can effectively reduce these symptoms. Studies found that acute exercise [10] and regular physical activities can induce physiological and psychological mechanisms that not only promote physical and psychological health but also improve physiological and cognitive functions, including memory and executive function [11–14]. Based on the symptoms of ADHD (impulsiveness and hyperactivity), combining exercise training with conventional treatment can increase the benefits. Exercise can be considered as a category of physical activity and refers to planned, structured, and repetitive physical activities that can increase or maintain an individual's physical fitness [15]. Most physical activities or exercise interventions in children with ADHD are clinical rehabilitation exercises to improve the motor coordination, cognitive function, and interpersonal skills or emotional disorders [16]. Planned physical exercises are beneficial for executive function, emotional regulation, spatial memory, learning performance, mood development, and interpersonal relationships [13,17], and can induce structural and functional neuroplasticity [18] in brain.

However, the above studies mostly examined the immediate or long-term benefits of exercise intervention and less analyze the neurophysiological and neuropsychological effects of exercise model, and exercise intensity. In addition, although inattention problems in 50% of the children with ADHD improve with age, impulsivity symptoms continue into adulthood [19].

To verify the findings, we collected ADHD-related physiological and psychological abnormalities and compiled studies on the benefits of exercise in children and adolescents with ADHD to provide a conceptual mechanism on exercise intervention [20–22]. Hence, we compiled the benefits of exercise in ADHD from the exercise intervention studies and discussed these results based on the neurophysiological framework presented. We cautiously provided exercise training suggestions for ADHD children, including exercise duration, exercise intensity, and exercise model for reference purposes.

Exercise and neurophysiology change

The core symptom of ADHD is neuropsychological deficit. When responding to external stimuli, abnormalities in

attention selection or maintenance occur, which cause response inhibition/delay. ADHD is also accompanied by neurophysiological deficits. Research on brain operation mechanisms found that ADHD is caused by physiological, structural, and functional abnormalities in the central nervous system [11]. Poor inhibitory function, dyspraxia, and spatial working memory of the central nervous system [23] are associated with insufficient dopamine and norepinephrine secretion caused by dysfunction in the frontostriatal circuits [24,25]. Moreover, functional magnetic resonance imaging (fMRI) studies found that ADHD is associated with poor activation of the cerebrum, thalamus, and cerebellum [26,27]. We included studies on neurophysiological improvement in ADHD caused by exercise intervention to examine it can improve these neurophysiological mechanisms.

When exercise intensity is moderate–high, the body activates neurophysiological responses to induce the synthesis of neurotransmitters, secrete brain-derived neurotrophic factor (BDNF), and increase the blood flow to the brain, thereby improving neuroplasticity and enhancing information-processing capacity [28]. These effects can alleviate ADHD symptoms and their comorbidities [29] and facilitate neural growth and regulation in the brains of children with ADHD. The mechanisms by which a single-bout of exercise affects the nervous system include vagal activity and anti-pain and anti-depression neurotransmitters (such as serotonin), which are stress-decreasing hormones. Single-bout of exercises can enhance cognitive function through instantaneous neurochemical reactions, such as increasing the secretions of BDNF and the levels of synaptic proteins, glutamate receptors, and insulin-like growth factor availability, all of which seem to improve cell proliferation and neuroplasticity [30,31]. Aerobic exercise appears to have more immediate and long-term effects [21,29,31]. Tantillo et al. conducted a study on the benefits of single-bout of exercises on children with ADHD. They measured spontaneous eye blink rates, acoustic startle eye blink response, and motor inhibition to indirectly prove that single-bout of exercise at 65%–75% oxygen consumption (VO_2 peak) can increase dopamine concentration in the brain [32].

Recent studies found that exercise intensity is critical for inducing neuroplasticity and BDNF secretion. A study established that lactic acid and BDNF produced by moderate–high intensity exercise is associated with neuroplasticity. In brain metabolism, lactic acid plays an extremely complex role. After moderate–high intensity exercise, peripheral lactate levels increase brain BDNF concentration, which in turn increases neuroplasticity [18].

Therefore, aerobic exercise can induce the secretion of neurotransmitters such as serotonin and dopamine in the brain, increase brain blood flow and circulation, enhance the metabolism, and activate the central nervous system. Furthermore, moderate–high intensity exercise can promote BDNF synthesis, enhance neuroplasticity, and decrease the risk of nervous system disorders.

Exercise and cognitive function change

Exercise not only improves the cognitive function in normal children but also has positive and significant effects in

children with neuropsychiatric disorder [6,14,33]. Present studies showed that intervention of aerobic and exercise stretching may be helpful for cognitive function and behavior in children with ADHD and comorbid with Tourette disorders [14]. Some studies showed a trend that chronic physical exercise appears to be beneficial at higher intensity for ADHD children comorbid with Tourette syndrome; however, the effects of acute physical exercise are intensity-dependent, where low-intensity aerobic exercise may alleviate and high-intensity exercise may increase tic syndromes [34,35]. A study showed that aerobic exercise may reduce the tic frequency in children and young people with Tourette Syndrome. This finding suggests that aerobic exercise can be a useful intervention for improving self-regulation of tics, through neurophysiology change and enhancements in associated cognitive control function [35].

The immediate effects of exercise on cognitive function have attracted increasing attention in recent years. Meta-analyses found that high-intensity exercise increases wakefulness and improves various cognitive functions. However, single-bout of exercises may not result in long-term cognitive function changes or have direct effects on impulsive behaviors and learning outcomes in children with ADHD [11,36]. Among these benefits, increase in executive function is a significant immediate effect after exercise intervention. Etnier et al. conducted a study comparing 8–12-year-old children with ADHD who underwent moderate-intensity aerobic exercise and children with ADHD who watched videos for 20 min. The results indicated that the single-bout of moderate-intensity aerobic exercise can improve executive function in children with ADHD [37]. This finding shows that moderate-intensity exercise can decrease impulsive behavior and inattention in children with ADHD. Even though the immediate cognitive benefits of exercise are limited, these benefits may gradually accumulate over time. Such effects reflect the positive correlation between cognition and physical activity, and this benefit will also lead to changes in cognitive function after long-term training [11].

Drollette et al. employed electroencephalography (EEG) to observe inhibition control in children during the Flanker task test. They found that there was an immediate improvement in response conflict and the speed of stimulus classification in children who received exercise intervention. However, the degree of improvement was greater in children with lower inhibitory control capacity, and these children benefited the most from single-bout of exercises [38]. These benefits are more significant in ADHD children with inhibitory dysregulation, which means that ADHD has a pervasive and extreme characteristic. Therefore, a single-bout of exercises have greater immediate effects on cognitive functions [11]. This effect may be attributed to the fact that single-bout of moderate-intensity exercises induce regulatory and attention resources and effectively allocate them as well as decrease the load on neural activities associated with conflict detection. These effects may be amplified in children with lower cognitive functions [38].

In comparison, it was found that among ADHD children with lower inhibitory control capacity, those with higher aerobic fitness or greater activity level demonstrated a better inhibitory control. In a study, boys with ADHD were asked to

wear an accelerometer for 1 week to evaluate their daily physical activity level. The results indicated that children with moderate–high physical activity had better executive function performance, which was the most significant aspect in the results of Tower of London planning task. This finding suggested that children with higher physical activity have better executive function performance in working memory, inhibitory control, and information-processing speed [39]. However, these correlations change with age. Brassell et al. found that cardiopulmonary endurance is positively correlated with inhibitory control in children with high ADHD risk. Such children have better aerobic fitness and inhibitory function and this phenomenon is more significant in younger pre-school children. However, aerobic endurance, physical fitness, and inhibitory function improve with age. Therefore, aerobic exercise intervention is also an important prevention strategy for children with ADHD risk [4].

Moreover, the duration of benefits generated by exercise is also important for lifestyle and learning strategies in children with ADHD. A single-bout of moderate intensity aerobic exercises and inhibitory control tests were performed on these children. The data showed that response accuracy and conflict detection significantly improved within 60 min after the moderate-intensity exercise regardless of the task difficulty. This result signifies that the benefits of single-bout of aerobic exercise intervention in inhibitory control can last for 60 min in children with ADHD [10].

In summary, the intervention of single-bout of exercise offers immediate and persistent benefits in cognitive function, and long-term exercise training can effectively improve overall fitness and exert long-lasting effects on cognitive function in children. A meta-analysis collected 314 studies. After screening and filtering, 31 studies were left. The results showed that exercise intervention can effectively increase the executive function in children and adolescents with ADHD (SMD = 0.611, 95% CI [0.386–0.836], $p < 0.01$), of which inhibitory control ($g = 0.761$, 95% CI [0.376, 1.146], $p < 0.01$) and cognitive elasticity ($g = 0.780$, 95% CI [0.331, 1.228], $p < 0.001$) demonstrated the most significant improvements. Both single bout of exercise intervention and long-term exercise training have positive benefits, and long-term moderate-intensity exercise is currently the most recommended model for children with ADHD [12,40].

Exercise model and exercise intensity

An analysis of exercise models found that both aerobic and anaerobic exercises have potential short-term and long-term benefits in cognition, social behavior, emotions, and physical/mental outcomes in patients with ADHD. Aerobic exercises seem to have a greater potential for immediate as well as long-lasting cognition and behavioral effects in children with ADHD [31]. In a study on attention and executive function in children with ADHD and normal children and adolescents, the type of exercise involved was mostly moderate-intensity cycling or treadmill exercise, and the results showed that both cycling and treadmill exercises had immediate benefits for ADHD [41]. There are many types of aerobic exercise training, and intensity is the key. Owing to the characteristics,

impulsiveness, lack of motivation, impatience, and persistence of children with ADHD, interval training is the most recommended form of exercise. Therefore, the following sections are divided into aerobic interval training and anaerobic exercise. There are diverse types of anaerobic exercise, and the effects of perceptive motor training and mediation training on children with ADHD are covered in the following sections.

Aerobic with interval training

Interval training is a type of training involves repeated bouts of high intensity effort followed by varied recovery times [15]. This exercise model is suitable for natural running and jumping exercises and variable alternating fast and slow movements, which is an interesting and low-cost training method with no side effects. Clinical exercise therapy in ADHD often employs moderate–high intensity interval training and mainly uses second-maximum intensity and less time to achieve the results that are close to an aerobic training [42]. According to the definition of American College of Sports Medicine on exercise prescription, moderate intensity is 65%–75% of the maximum heart rate of an individual (220-age) [15]. When moderate-intensity exercise is performed for 20–30 min, the body will enter the aerobic exercise stage. The high intensity interval training (HIIT) refers to an exercise intensity load that is >90% of the maximal heart rate or Rated Perceived Exertion (RPE) Scale > 17 and the intense work periods may range from 15 s to 4 min long. The recovery periods may last equally as long as the work periods (1:1 training) and are usually performed at 40%–50% of a person's estimated maximal heart rate [42]. The workout continues with the alternating work and relief periods about 20 min.

Boys with ADHD aged 7–15 years were given a single session of high-intensity training (HIIT) with two times 10-min sessions with a 1-min break in between, and the results showed that 20 min of high-intensity exercise significantly improved cognitive function and sustained attention [28]. When the exercise intensity was moderately high, ADHD symptoms and other comorbidities significantly decreased [29]. This result shows that short periods of HIIT can effectively increase attention, decrease impulsivity, and improve some cognitive functions in children with ADHD. However, long periods of HIIT also improved physical fitness, motor coordination, self-confidence, and interpersonal relationships in boys with ADHD, particularly subjective attention [22] and response inhibition function [43].

To increase the motivation and participation of children with ADHD, the content of exercise training should include game elements and employ psychological techniques. It is also important to provide words of affirmation and positive encouragement [16,44]. Therefore, some studies employed combined exercise training to increase training completion in children ADHD. In a study on 37 children with ADHD aged 8–11 years, 8 weeks of combined exercise training was given. The training course included perceptual motor training and 20 min of moderate-intensity interval training. After 8 weeks, complex information processing capacity and executive function improved significantly in children with ADHD [21]. Another study provided 8 weeks of aquatic exercise to

children with ADHD (twice a week, 90 min per session). The results showed that accuracy and motor skill coordination, which are related to impulsivity tests, improved significantly in the exercise group after the intervention. This result showed that planned quantitation and qualitative exercise improve inhibition behavior in children with ADHD [45]. Therefore, the planning of exercise model and exercise intensity based on age, behavioral characteristics, and motor skills of children with ADHD have positive effects on attention and executive function.

Perceptive motor training and meditation

Perceptive motor training is an exercise training model that is often performed in children. The primary objective of perceptive motor training is to promote coordination between the perception system and motor control, emphasize sensory stimulation, train the vestibular sensation and proprioception, tactility, judgment of visual and auditory spaces, regulation of muscle tension changes, and visuomotor coordination. The input of diverse perceptual information to the central nervous system during exercise organizes and integrates sensory information, which leads to neuroplasticity in nerve cells and synaptic connections; furthermore, strengthening the sensory-motor base contributes to the attention performance [44]. A study was conducted on 14 children with ADHD with a mean age of 8 years, where subjects underwent 30 min of rhythmic dancing. The content of the activity was to dance along with music and included vestibular, balance, tactile, proprioceptive, and rhythmic movement elements. This exercise emphasized physical coordination and rhythm, and the exercise intensity was 60% of the maximum heartbeat. The results found that attention was improved in children with ADHD after the rhythmic movements [36].

The effects of mindfulness and mediation on emotional regulation and attention have attracted immense attention in recent years. Some studies examined the effects of mindfulness training or mediation on ADHD children and found that the attention, awareness, and self-control ability of children with ADHD are significantly improved after the trainings of mindfulness and mediation [46,47]. Two meta-analyses were performed, and one of them collected 4 studies on the benefits of mediation, relaxation training, and yoga in 83 children with ADHD. Owing to the limited number of studies, small sample size, and the high risk of bias, a conclusion on the effectiveness of mediation on ADHD could not be reached [48]. The other study compiled 16 studies and performed a meta-analysis. The results found that many studies did not employ a control group, and a conclusion on the benefits of mindfulness and mediation on ADHD could not be reached [49]. There are many non-drug intervention methods for ADHD, but empirical studies are required to ascertain if there is evidence for efficacy. Che et al. (2021) compiled 83 independent studies on ADHD involving 4996 subjects and 14 non-drug treatments in a meta-analysis. These studies included (1) mediation and awareness; (2) exercise training; (3) vitamins and mineral supplements; and (4) cognitive behavioral therapy. The results found that physical exercise training is effective and has the most stable effects in improving the

symptoms of attention deficit. This method was followed by mediation, cognitive therapy, and cognitive behavioral therapy, which are effective auxiliary tools [50].

In summary, lifestyle arrangements such as physical activities or exercise are very important in children with ADHD, which includes those suspected of high-risk ADHD and those with lower cognitive processing speed. Systematic and planned moderate-high exercise courses should be administered as soon as possible [17,19]. These interventions may help alleviate inattention, hyperactivity/impulsivity symptoms, and problems in interpersonal interactions to enhance the adaptivity of the students in learning.

Conclusion

Appropriate exercise intervention can not only augment the sensorimotor skills but also increase self-confidence and improve communication and social interaction skills in children. Exercise is an important tool for children with ADHD in the developmental phase. Aerobic exercise or perceptual motor training is beneficial to children with ADHD. Both single-bout and long-term exercises can improve the blood flow to the brain, enhance information processing capacity and attention, decrease impulsiveness, and increase inhibitory control, thereby improving interpersonal relationships. With regard to exercise prescription, planned and combined exercise courses should be selected, and the contents should emphasize exercise intensity and perceptual motor exercises combined with cognitive tasks (such as motor planning skills) [51]. The teaching plan should include game content. This approach can effectively improve the perceptual and cognitive functions of children with ADHD.

We hope that the purpose of current studies is attracting more scientific attention to the topic and provides important directions for future researches by establishing a positive effect of exercise. If the effects of precise exercise for ADHD are better substantiated in the future, we expect to have a powerful complementary or alternative treatment. Finally, it is recommended that for children suspected of having a high risk for ADHD, appropriate exercise training can be integrated into the overall ADHD intervention plan.

Conflicts of interest

There is no competing interest among the authors.

REFERENCES

- [1] Thapar A, Cooper M, Rutter M. Neurodevelopmental disorders. *Lancet Psychiatr* 2017;4:339–46.
- [2] Posner J, Polanczyk GV, Sonuga-Barke E. Attention-deficit hyperactivity disorder. *Lancet* 2020;395:450–62.
- [3] American Psychiatric Association. Diagnostic and statistical manual of mental disorders. 5th ed. USA: American Psychiatric Association; 2013.
- [4] Brassell AA, Shoulberg EK, Pontifex MB, Smith AL, Delli Paoli AG, Hoza B. Aerobic fitness and inhibition in young children: moderating roles of ADHD status and age. *J Clin Child Adolesc Psychol* 2017;46:646–52.
- [5] Egger H, Kondo D, Angold A. The epidemiology and diagnostic issues in preschool attention-deficit/hyperactivity disorder: a review. *Infants Young Child* 2006;19:109–22.
- [6] Liu WY, Wang HS, Hsu LY, Wong AM, Chen CL, Lien HY. Health-related physical fitness management for a child with Tourette syndrome. *Chang Gung Med J* 2011;34:4–9.
- [7] Sharma A, Couture J. A review of the pathophysiology, etiology, and treatment of attention-deficit hyperactivity disorder (ADHD). *Ann Pharmacother* 2014;48:209–25.
- [8] Anastopoulos AD, Smith TF, Garrett ME, Morrissey-Kane E, Schatz NK, Sommer JL, et al. Self-regulation of emotion, functional impairment, and comorbidity among children with AD/HD. *J Atten Disord* 2011;15:583–92.
- [9] Hodgens JB, Cole J, Boldizar J. Peer-based differences among boys with ADHD. *J Clin Child Psychol* 2000;29:443–52.
- [10] Yu CL, Hsieh SS, Chueh TY, Huang CJ, Hillman CH, Hung TM. The effects of acute aerobic exercise on inhibitory control and resting state heart rate variability in children with ADHD. *Sci Rep* 2020;10:19958.
- [11] Christiansen L, Beck MM, Bilenberg N, Wienecke J, Astrup A, Lundbye-Jensen J. Effects of exercise on cognitive performance in children and adolescents with ADHD: potential mechanisms and evidence-based recommendations. *J Clin Med* 2019;8:841.
- [12] Liang X, Li R, Wong SHS, Sum RKW, Sit CHP. The impact of exercise interventions concerning executive functions of children and adolescents with attention-deficit/hyperactive disorder: a systematic review and meta-analysis. *Int J Behav Nutr Phys Activ* 2021;18:68.
- [13] Schwarck S, Schmicker M, Dordevic M, Rehfeld K, Müller N, Müller P. Inter-individual differences in cognitive response to a single bout of physical exercise-A randomized controlled cross-over study. *J Clin Med* 2019;8:1101.
- [14] Wang HS, Kuo MF, Stern JS. Possible role of repetitive practice of activities requiring reflexive responses in the treatment of Tourette's disorder. *Chang Gung Med J* 2011;34:650–3.
- [15] Liguori G, (ACSM) ACoSM. ACSM's guidelines for exercise testing and prescription. 11th ed. Philadelphia: Wolters Kluwer; 2021.
- [16] Huang JH, Yeh CP, Chan YS. Effect of physical activity on behavior and cognition in children with attention deficit/hyperactivity disorder [effect of physical activity on behavior and cognition in children with attention deficit/hyperactivity disorder]. *Sports Res Rev* 2017:43–51.
- [17] Hoza B, Martin CP, Pirog A, Shoulberg EK. Using physical activity to manage ADHD symptoms: the state of the evidence. *Curr Psychiatr Rep* 2016;18:113.
- [18] Müller P, Duderstadt Y, Lessmann V, Müller NG. Lactate and BDNF: key mediators of exercise induced neuroplasticity? *J Clin Med* 2020;9:1136.
- [19] Hoza B, Shoulberg EK, Tompkins CL, Martin CP, Krasner A, Dennis M, et al. Moderate-to-vigorous physical activity and processing speed: predicting adaptive change in ADHD levels and related impairments in preschoolers. *JCPP (J Child Psychol Psychiatry)* 2020;61:1380–7.
- [20] Kamp CF, Sperlich B, Holmberg HC. Exercise reduces the symptoms of attention-deficit/hyperactivity disorder and improves social behaviour, motor skills, strength and neuropsychological parameters. *Acta Paediatr* 2014;103:709–14.
- [21] Chan YS, Ho CS. Reaction performance improvement in children with ADHD through adapted physical activity? A pilot study. *Dtsch Z Sportmed* 2021;72:21–7.
- [22] Meßler CF, Holmberg HC, Sperlich B. Multimodal therapy involving high-intensity interval training improves the physical fitness, motor skills, social behavior, and quality of

- life of boys with ADHD: a randomized controlled study. *J Atten Disord* 2018;22:806–12.
- [23] Lipszyc J, Schachar R. Inhibitory control and psychopathology: a meta-analysis of studies using the stop signal task. *J Int Neuropsychol Soc* 2010;16:1064–76.
- [24] Halperin JM, Healey DM. The influences of environmental enrichment, cognitive enhancement, and physical exercise on brain development: can we alter the developmental trajectory of ADHD? *Neurosci Biobehav Rev* 2011;35:621–34.
- [25] Durston S, van Belle J, de Zeeuw P. Differentiating frontostriatal and fronto-cerebellar circuits in attention-deficit/hyperactivity disorder. *Biol Psychiatr* 2011;69:1178–84.
- [26] Ivanov I, Bansal R, Hao X, Zhu H, Kellendonk C, Miller L, et al. Morphological abnormalities of the thalamus in youths with attention deficit hyperactivity disorder. *Am J Psychiatr* 2010;167:397–408.
- [27] Connolly AJ, Rinehart NJ, Fielding J. Saccade adaptation in young people diagnosed with attention deficit hyperactivity disorder combined type. *Neuroscience* 2016;333:27–34.
- [28] Medina JA, Netto TL, Muszkat M, Medina AC, Botter D, Orbetelli R, et al. Exercise impact on sustained attention of ADHD children, methylphenidate effects. *Atten Defic Hyperact Disord* 2010;2:49–58.
- [29] Ng QX, Ho CYX, Chan HW, Yong BZJ, Yeo WS. Managing childhood and adolescent attention-deficit/hyperactivity disorder (ADHD) with exercise: a systematic review. *Compl Ther Med* 2017;34:123–8.
- [30] Halperin JM, Bédard AC, Curchack-Lichtin JT. Preventive interventions for ADHD: a neurodevelopmental perspective. *Neurotherapeutics* 2012;9:531–41.
- [31] Den Heijer AE, Groen Y, Tucha L, Fuermaier AB, Koerts J, Lange KW, et al. Sweat it out? The effects of physical exercise on cognition and behavior in children and adults with ADHD: a systematic literature review. *J Neural Transm* 2017;124:3–26.
- [32] Tantillo M, Kesick CM, Hynd GW, Dishman RK. The effects of exercise on children with attention-deficit hyperactivity disorder. *Med Sci Sports Exerc* 2002;34:203–12.
- [33] de Greeff JW, Bosker RJ, Oosterlaan J, Visscher C, Hartman E. Effects of physical activity on executive functions, attention and academic performance in preadolescent children: a meta-analysis. *J Sci Med Sport* 2018;21:501–7.
- [34] Kim DD, Warburton DER, Wu N, Barr AM, Honer WG, Procyshyn RM. Effects of physical activity on the symptoms of Tourette syndrome: a systematic review. *Eur Psychiatr* 2018;48:13–9.
- [35] Jackson GM, Nixon E, Jackson SR. Tic frequency and behavioural measures of cognitive control are improved in individuals with Tourette syndrome by aerobic exercise training. *Cortex* 2020;129:188–98.
- [36] Chen MY, Chen MH. Effect of acute rhythm movement on attention in children with attention deficit hyperactivity disorder [Effect of acute rhythm movement on attention in children with attention deficit hyperactivity disorder]. *Bull Sport Exerc Psychol Taiwan* 2018;18:59–76.
- [37] Etnier J, Smith A, Gapin J, Labban J. Physical activity and cognitive performance in children with attention deficit hyperactivity disorder (ADHD)-Symposium overview. *J Sport Exerc Psychol* 2009;31:S11.
- [38] Drollette ES, Scudder MR, Raine LB, Moore RD, Saliba BJ, Pontifex MB, et al. Acute exercise facilitates brain function and cognition in children who need it most: an ERP study of individual differences in inhibitory control capacity. *Dev Cogn Neurosci* 2014;7:53–64.
- [39] Gapin J, Etnier JL. The relationship between physical activity and executive function performance in children with attention-deficit hyperactivity disorder. *J Sport Exerc Psychol* 2010;32:753–63.
- [40] Vysniauske R, Verburgh L, Oosterlaan J, Molendijk ML. The effects of physical exercise on functional outcomes in the treatment of ADHD: a meta-analysis. *J Atten Disord* 2020;24:644–54.
- [41] Piepmeier AT, Shih CH, Whedon M, Williams L, Davis M, Henning D, et al. The effect of acute exercise on cognitive performance in children with and without ADHD. *J Sport Health Sci* 2015;4:97–104.
- [42] Meßler CF. Auswirkungen sportlicher Aktivitäten bei Kindern mit Aufmerksamkeits-Defizit-Hyperaktivitäts-Störung (ADHS) unter besonderer Betrachtung von Hochintensivem Intervalltraining als innovativen, therapeutischen Ansatz [Effects of physical activities in children with attention deficit hyperactivity disorder (ADHD) with reference to high intensity interval training as an innovative therapeutic approach]. *Bewegungstherap Gesundheitssport* 2019;35:88–92.
- [43] Smith AL, Hoza B, Linnea K, McQuade JD, Tomb M, Vaughn AJ, et al. Pilot physical activity intervention reduces severity of ADHD symptoms in young children. *J Atten Disord* 2013;17:70–82.
- [44] Chan YS, Ho CS, Wu HH. Psychophysiologic mechanism and benefits of exercise training on children with attention deficit hyperactivity disorder [psychophysiologic mechanism and benefits of exercise training on children with attention deficit hyperactivity disorder]. *Sports Res Rev* 2011:69–75.
- [45] Chang YK, Hung CL, Huang CJ, Hatfield BD, Hung TM. Effects of an aquatic exercise program on inhibitory control in children with ADHD: a preliminary study. *Arch Clin Neuropsychol* 2014;29:217–23.
- [46] Schmiedeler S. [Mindfulness-based intervention in attention-deficit-/hyperactivity disorder (ADHD)]. *Z Kinder JugendPsychiatr Psychother* 2015;43:123–31.
- [47] Meppelink R, de Bruin EI, Bögels SM. Meditation or Medication? Mindfulness training versus medication in the treatment of childhood ADHD: a randomized controlled trial. *BMC Psychiatr* 2016;16:267.
- [48] Krisanaparakornkit T, Ngamjarus C, Witoonchart C, Piyavhatkul N. Meditation therapies for attention-deficit/hyperactivity disorder (ADHD). *Cochrane Database Syst Rev* 2010;2010:Cd006507.
- [49] Evans S, Ling M, Hill B, Rinehart N, Austin D, Sciberras E. Systematic review of meditation-based interventions for children with ADHD. *Eur Child Adolesc Psychiatr* 2018;27:9–27.
- [50] Che X, Jong-Hwan C, Shang X. Comparative efficacy and acceptability of nonpharmacotherapy in the treatment of inattention for ADHD: a network meta-analysis. *Complexity* 2021;2021:9435262.
- [51] Neudecker C, Mewes N, Reimers AK, Woll A. Exercise interventions in children and adolescents with ADHD: a systematic review. *J Atten Disord* 2019;23:307–24.