Li and Zhang *BMC Sports Science, Medicine and Rehabilitation* (2025) 17:80
https://doi.org/10.1186/s13102-025-01142-1

BMC Sports Science, Medicine and Rehabilitation

**RESEARCH** **Open Access**

# The effect of exercise intervention on balance and executive function in children with autism spectrum disorder: a meta-analysis

Haixia Li[1] and Ruiyun Zhang[2*]

## Abstract

**Objective** This study primarily evaluated the the effects of exercise intervention on balance and executive function in children with autism spectrum disorder (ASD).

**Methods** Search for eligible studies through four databases, and then proceed with screening. The inclusion criteria are as follows: (1) Children with ASD; (2) Age 3–18 years; (3) Randomised Controlled Trial; (4) The intervention group received exercise training; (5) Conducted pre- and post-test, which include balance and executive function. Use the Cochrane bias risk assessment tool to evaluate the quality of the selected study. Select Standardized Mean Difference (SMD) as the appropriate effect scale index.

**Results** Twelve of the selected articles involved 288 males and 108 females. The findings demonstrated that the exercise group (EG) benefited more from the improved balance than its control group (CG) counterpart [SMD = 0.86 (0.56, 1.16), $p < 0.05$, $I^2 = 37\%$]. Furthermore, subgroup analysis revealed that exercise interventions lasting over eight weeks significantly enhanced balance [SMD = 1.19 (0.79, 1.58), $p < 0.05$, $I^2 = 17\%$]. However, exercise interventions lasting less than or equal to 8 weeks did not have a significant impact on balance [SMD = 0.41 (−0.06, 0.87), $p = 0.09$, $I^2 = 0\%$].

**Conclusion** Exercise interventions can better improve the balance and behavioural inhibition of children with ASD compared to CG. Nevertheless, physical training prescribed for more than eight weeks led to a more significant improvement in balance than interventions performed for shorter periods.

**Keywords** Exercise interventions, Balance, Autism spectrum disorder, Children

---

*Correspondence:
Ruiyun Zhang
sdzhangruiyun@163.com
[1]School of Sport Management, Shandong Sport University, Lichen District, Jinan city 250102, Shandong, China
[2]School of Sport Art, Shandong Sport University, Lichen District, Jinan city 250102, Shandong, China

## Introduction

Social communication and motor behaviour with limited, repetitive sensory conduct are the predominant fundamental attributes of autism spectrum disorder (ASD) [1]. Physically, the illness can manifest as compromised executive function and balance, leading to postural stability issues and increased injury risks [2, 3–4]. The postural symptoms have also been demonstrated to continue into adulthood and are distinguished by an abnormally early plateau during adolescence [5].

Children participating in different exercise intervention programmes can have improved motor skills, balance, and fitness levels [6–8]. Exercise reportedly positively affects and assists children with ASD with daily tasks requiring strength, endurance, flexibility, and stability [9]. Furthermore, physical training can boost the self-confidence of the children [10].

Nine weeks of psychomotor [11] and 12 weeks of structured circular [12] trainings have led to longer-term alterations in postural stability in children with ASD. The data offer preliminary evidence that balance can be enhanced in individuals suffering from the disorder. Nevertheless, Milajerdi et al. revealed that an eight-week motion-sensing tennis game training did not improve the balance skills of children with ASD [6]. Speculation may be due to differences in evaluation methods and shorter intervention times. As such, the influence of exercise on children with ASD remains unclear.

A meta-analysis study involving 15 reports focusing on balance parameters indicated that any physical intervention strategy is advantageous for children with ASD [7]. Nonetheless, the reviewed studies did not employ randomised controlled trials (RCT). On the one hand, RCT outperform other research designs in minimizing bias and establishing causal relationships. On the other hand, The reliability of the results of the single arm meta-analysis is also low due to children's rapid growth and development. As such, this study included RCT reports to determine the effects of exercise intervention on balance and executive function in children with ASD.

## Materials and methods

### Protocol and registration

The current study registered the review procedure applied with the International Prospective Register of Systematic Reviews on December 17th, 2024 (registration number: CRD 42024628585).

### Data sources and study selection

During the initial phases of this study, Scopus, PubMed, Web of Science, and EBSCO databases were searched, spanning January 2004 to December 2024. The search was completed on December 18th, 2024. The terms "ASD", "autism", "training", "exercise", "balance", "children", and "executive function" were applied during the searches. The search plan and outcomes acquired from each database are summarised in Appendix A.

Two investigators independently analysed each selected title and abstract before assessing complete papers according to the inclusion and exclusion criteria. The criteria are discussed in next section of this article. The main information extracted from the included literature includes age, gender, intervention duration, exercise protocol, and index. Any disputes among the investigators were resolved by inviting a third investigator to attain a consensus. Figure 1 illustrates the article selection process employed in the current study. This systematic review and meta-analysis was conducted per the guideline suggested by the preferred reporting items for systematic reviews and meta-analyses (PRISMA).

### Inclusion and exclusion criteria

For this review, six inclusion criteria were set. Only articles involving ASD patients between 3 and 18 years old were included. The reports must also employ RCT and exercise training as the intervention and record balance and behavioural inhibition (BI), flexibility (FL) and working memory (WM) as the outcomes. The main methods used to assess balance were single leg standing time, Movement Assessment Battery for Children scale, Berg Balance Scale, Peabody motor development scale scores. The main methods of assessing executive functioning include Flanker task, Wisconsin Card Sorting Test, Hearts & Flowers test, The Behavior Rating Inventory of Executive Function and Go/No-Go task. Furthermore, only full-text papers in English were reviewed. Conversely, grey literature, including abstracts, conference proceedings, and poster presentations, was not considered.

### Quality assessment

The quality of the selected reports in this study was established with the Cochrane risk of bias tool [13]. The evaluation encompassed assessment outcome and participants and personnel blinding, incomplete data, random sequence generation, selective reporting, and allocation sequence concealment [14]. In this study, two co-authors analysed the quality of each report independently. Meanwhile, another author assisted in resolving disagreements to attain a consensus. The quality of each article was then rated "Yes", "No", or "Unclear".

### Risk of bias analysis

This meta-analysis performed sensitivity evaluation by excluding an article at a time to determine the stability of the findings. Subsequently, funnel plots were utilised to establish publication bias of the reviewed articles.

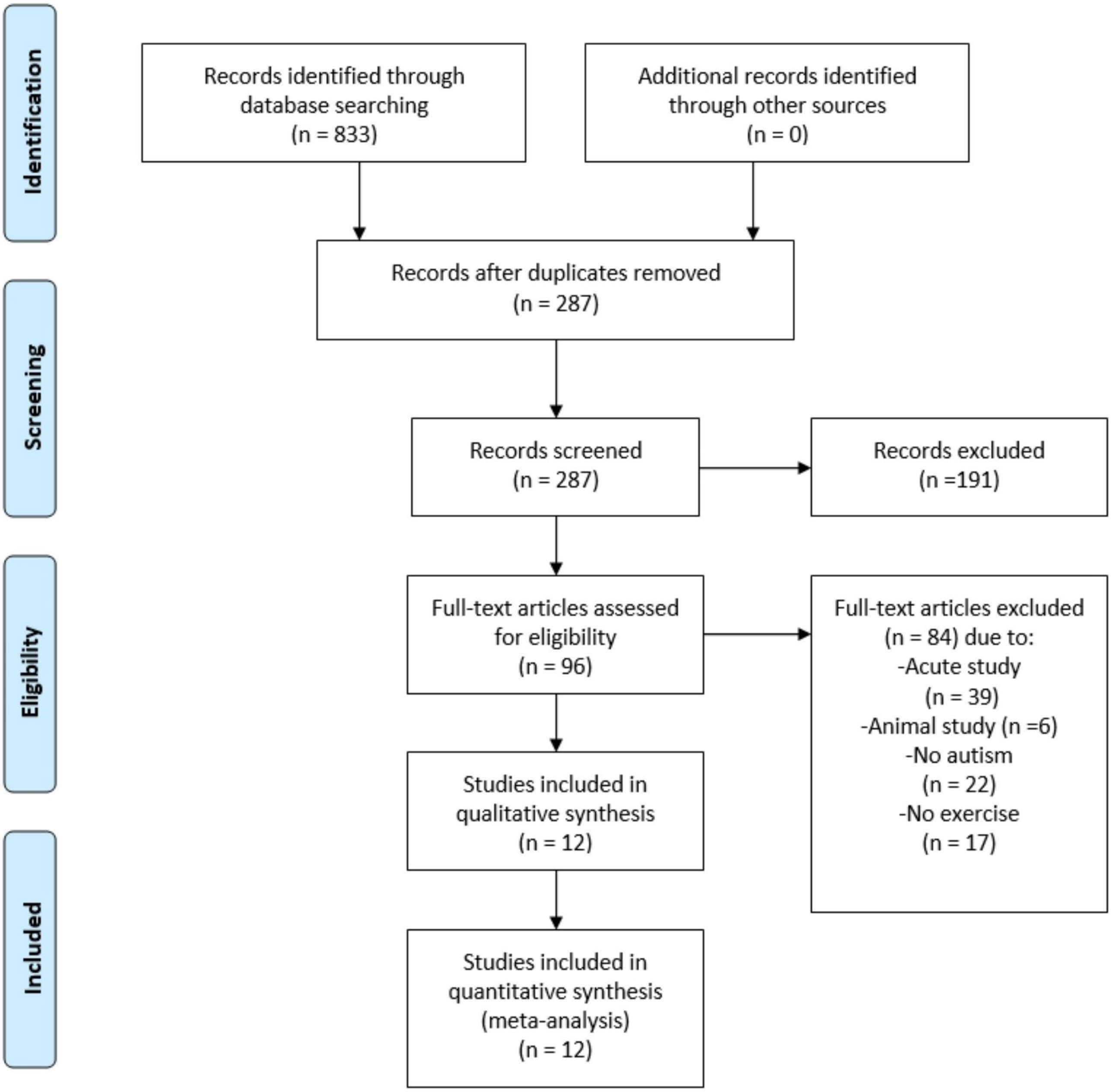


**Fig. 1** Flow diagram of the search results using the Preferred Reporting Items for Systematic Reviews and Meta-analysis (PRISMA)

### Data evaluation

Review Manager (RevMan) version 5.4.1 (The Cochrane Collaboration, Copenhagen, 2020) was employed in this review to determine the influences of the interventions. The procured data were then standardised by converting the median (range) figures into mean ± standard deviation. The data conversion is carried out on specialized online websites(http://vassarstats.net/median_range.html). If relevant data were undisclosed, the authors of the papers were formally emailed for clarification.

Heterogeneity between outcomes was determined by statistical analysis of $I^2$, which indicates the level of heterogeneity between the studies under review; if $I^2$ is less than 50%, it represents less heterogeneity and a fixed-effects model can be used. On the contrary, $I^2$ greater than 50% represents greater heterogeneity and a random effects model is used. The funnel plot method was also applied to assess publication bias analysis, while the mean difference was determined through the Forest plot technique. The uncertainty level for this study was at a 95% confidence interval (CI).

## Results

### Eligibility of studies

Table 1 lists the 12 articles that evaluated the influences of exercise on balance and executive functions in children with ASD. All reviewed reports only recorded baseline and final data post-intervention. The studies were also ethically approved by their respective institutions. Furthermore, the two researchers recorded a 0.94 Cohen kappa coefficient.

Twelve of the selected articles involved 288 males and 108 females. Among the reviewed publications, eight documented balance aspects and five reported the executive function. Based on the results, the studies were conducted at a minimum of 13 weeks and a 5-month maximum intervention period.

### Quality assessment

The selected articles recorded a relatively notable quality, as demonstrated in Fig. 2. Most of the papers (67.9%) also exhibited a low bias risk. Conversely, a small percentage of the articles (11.9%) indicated a significant bias risk, while the remaining reports (20.2%) were unclear.

### Quantitative synthesis

The influences of the intervention on the balance (Fig. 3) among children with ASD in the exercise group (EG) and control group (CG) were compared in eight selected studies [6, 11, 12, 15–19]. The findings demonstrated that the EG benefited more from the improved balance than its CG counterpart [SMD, 0.86 (0.56, 1.16), $p < 0.05$, $I^2 = 37\%$]. Furthermore, subgroup analysis revealed that exercise interventions lasting over eight weeks significantly enhanced balance [SMD, 1.19 (0.79, 1.58), $p < 0.05$, $I^2 = 17\%$]. However, exercise interventions lasting less than or equal to 8 weeks did not have a significant impact on balance [SMD, 0.41 (−0.06, 0.87), $p = 0.09$, $I^2 = 0\%$].

The effects of the interventions on the EG and CG on BI (Fig. 4a), FL (Fig. 4b), and WM (Fig. 4c) were compared in four [20–23], three [6, 20, 21] and two [20, 22] of the articles reviewed, respectively. The findings demonstrated that the EG recorded superior BI to the CG [SMD, −1.26 (−2.38, −0.14), $p < 0.05$, $I^2 = 92\%$]. Nonetheless, no considerable variations were documented between the groups regarding FL [SMD, 0.95 (−0.02, 1.92), $p = 0.06$, $I^2 = 85\%$] and WM [SMD, 2.96 (−1.83, 7.75), $p = 0.23$, $I^2 = 98\%$].

**Table 1** Characteristics of included studies

| Study | Age(y) | Gender | Duration | EX protocol | Index |
|---|---|---|---|---|---|
| Ansari 2021 | EG: 10.6 ± 2.5<br>CG: 10.8 ± 2.4 | 20 M | 10weeks; 2x/week | Aquatic training; orientation training, basic swimming skills and free swim; 60 min/session: 5 min warm-up, 15 min of directional training, 20 min of basic swimming skills, 15 min of free swimming, and 5 min cool-down. | BA |
| Arslan 2022 | 10.1 ± 0.3 | 14 M | 12weeks; 3x/week | Structured circular training; Balance, strength and jumping training; 60 min/session: 15 min warm-up, 40 min of main training and 5 min cool-down. | BA |
| Bo 2024 | EG: 8.4 ± 1.8<br>CG: 7.3 ± 1.4 | 21M5F | 9weeks; 3x/week | Combined training; locomotor skills: Run, jump, hop, skip, slide, gallop. Ball skills: catch, throw, dribble, hand strike, kick ball; 80 min/session. | BA |
| Draudviliene 2024 | 5.4 ± 0.8 | 16M4F | 5weeks; 3x/week | Combined training; Exercises on unstable surfaces, exercises with balls, throwing, catching, and hitting; 20 min/session. | BA |
| Haghighi 2023 | EG: 9.0 ± 1.3<br>CG: 8.1 ± 1.4 | 9M7F | 8weeks; 3x/week | Combined training; the ball game, rhythmic movements, and resistance exercises with elastic band; 60 min/session: 10 min warm-up, 40 min of combined training and 10 min cool-down. | BA |
| Hassen 2023 | EG: 8.1 ± 1.2<br>CG: 8.0 ± 1.4 | 15M15F | 9weeks; 2x/week | Psychomotor training; balance, cognitive stimulation games, fine and gross motor exercises, jumping and sensory integration activities, 5 min warm-up, 15 min of trampoline activity, 20 min of psychomotricity exercises and 5 min cool-down. | BA |
| Ji 2022 | EG: 13.1 ± 2.9<br>CG: 12.8 ± 2.7 | 35M31F | 6weeks; 3x/week | Xbox360 football training; RPE 10–13; Passing exercises, shooting exercises, and coordination exercise; 60 min/session. | BI, FL, WM |
| Milajerdi 2021 | EG: 8.2 ± 1.5<br>CG: 8.5 ± 1.4 | 35M2F | 8weeks; 3x/week | Videogame training; light-to-moderate intensity; Kinect tennis game demands balance, speed, strength, and reaction time; 35 min/session: 5 min warm-up, 25 min of game and 5 min cool-down. | BA, FL |
| Ozcan 2024 | EG: 4.8 ± 0.7<br>CG: 4.7 ± 0.8 | 32M2F | 12weeks; 2x/week | Motor intervention; training for motor skills, pre-academic skills and social skills; 60 min/session: 5 min warm-up, 5 min of targeted skills training, 40 min of basic movement skills and 10 min cool-down. | BA |
| Phung 2019 | EG: 9.1 ± 1.1<br>CG: 9.5 ± 1.1 | 26M6F | 13weeks; 2x/week | Mixed martial arts; Training for striking, glove drills and Combination (striking and grappling, offense/defense with a partner), 45 min/session: 5 min bow-in, 15 min warm-up, 20 min of main training and 5 min cool-down. | BI, FL |
| Tanksale 2020 | EG: 9.4 ± 1.3<br>CG: 9.5 ± 1.4 | 39M22F | 6weeks; 3x/week | Home-based yoga training, follow standardized instructional videos to practice yoga before bedtime, 10 min/session. | BI, WM |
| Tse 2019 | EG: 10.1 ± 1.2<br>CG: 9.8 ± 1.2 | 26M14F | 12weeks; 2x/week | Basketball skill learning intervention, moderate intensity, 45 min/session: 10 min warm-up, 30 min of basketball training and 5 min cool-down. | BI |

M = Male; F = Female; EG = Experimental group; CG = Control group; EX = Exercise; RPE = Ratings of perceived exertion; BA = Balance function; WM = Working memory; FL = Flexibility; BI = Behavioral inhibition

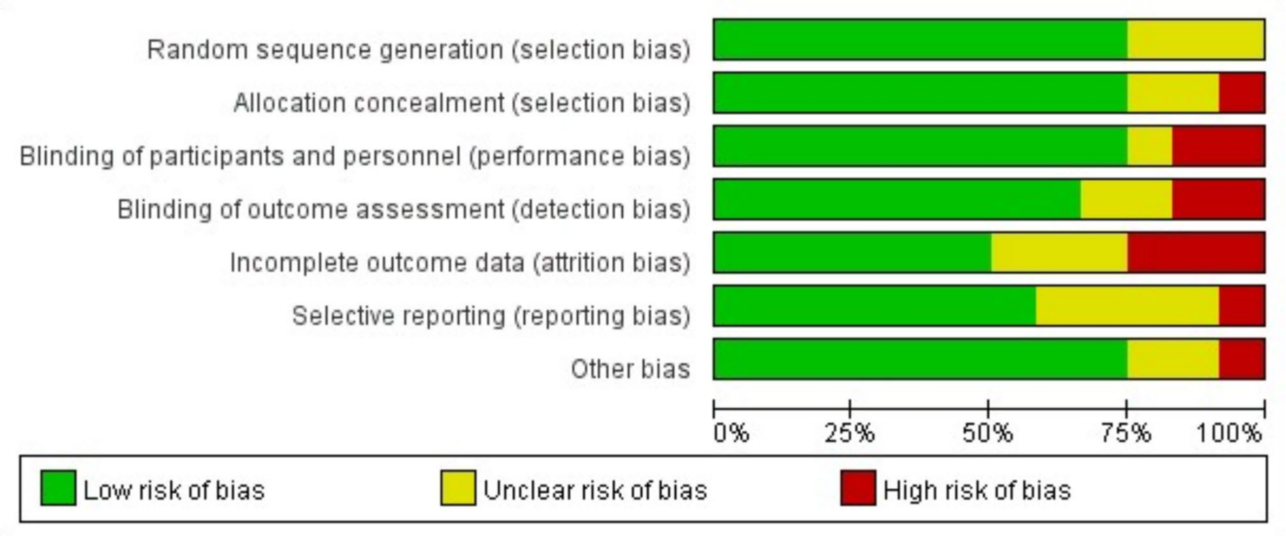
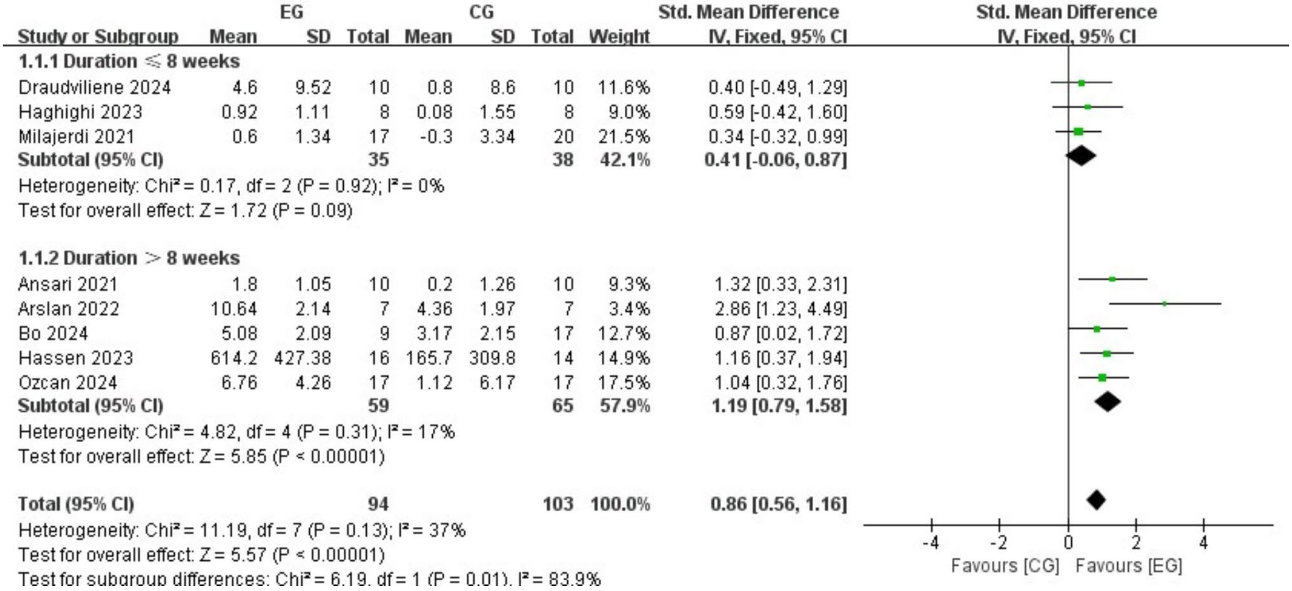


**Fig. 2** Analysis of risk of bias according to the Cochrane collaboration guideline



| | EG | | | CG | | | | Std. Mean Difference |
|---|---|---|---|---|---|---|---|---|
| **Study or Subgroup** | **Mean** | **SD** | **Total** | **Mean** | **SD** | **Total** | **Weight** | **IV, Fixed, 95% CI** |
| **1.1.1 Duration ≤ 8 weeks** | | | | | | | | |
| Draudviliene 2024 | 4.6 | 9.52 | 10 | 0.8 | 8.6 | 10 | 11.6% | 0.40 [-0.49, 1.29] |
| Haghighi 2023 | 0.92 | 1.11 | 8 | 0.08 | 1.55 | 8 | 9.0% | 0.59 [-0.42, 1.60] |
| Milajerdi 2021 | 0.6 | 1.34 | 17 | -0.3 | 3.34 | 20 | 21.5% | 0.34 [-0.32, 0.99] |
| **Subtotal (95% CI)** | | | **35** | | | **38** | **42.1%** | **0.41 [-0.06, 0.87]** |
| Heterogeneity: Chi² = 0.17, df = 2 (P = 0.92); I² = 0% | | | | | | | | |
| Test for overall effect: Z = 1.72 (P = 0.09) | | | | | | | | |
| **1.1.2 Duration > 8 weeks** | | | | | | | | |
| Ansari 2021 | 1.8 | 1.05 | 10 | 0.2 | 1.26 | 10 | 9.3% | 1.32 [0.33, 2.31] |
| Arslan 2022 | 10.64 | 2.14 | 7 | 4.36 | 1.97 | 7 | 3.4% | 2.86 [1.23, 4.49] |
| Bo 2024 | 5.08 | 2.09 | 9 | 3.17 | 2.15 | 17 | 12.7% | 0.87 [0.02, 1.72] |
| Hassen 2023 | 614.2 | 427.38 | 16 | 165.7 | 309.8 | 14 | 14.9% | 1.16 [0.37, 1.94] |
| Ozcan 2024 | 6.76 | 4.26 | 17 | 1.12 | 6.17 | 17 | 17.5% | 1.04 [0.32, 1.76] |
| **Subtotal (95% CI)** | | | **59** | | | **65** | **57.9%** | **1.19 [0.79, 1.58]** |
| Heterogeneity: Chi² = 4.82, df = 4 (P = 0.31); I² = 17% | | | | | | | | |
| Test for overall effect: Z = 5.85 (P < 0.00001) | | | | | | | | |
| **Total (95% CI)** | | | **94** | | | **103** | **100.0%** | **0.86 [0.56, 1.16]** |
| Heterogeneity: Chi² = 11.19, df = 7 (P = 0.13); I² = 37% | | | | | | | | |
| Test for overall effect: Z = 5.57 (P < 0.00001) | | | | | | | | |
| Test for subgroup differences: Chi² = 6.19, df = 1 (P = 0.01), I² = 83.9% | | | | | | | | |

**Fig. 3** Forest plot portraying the effects of EG vs. CG intervention on the balance

### Publication bias analysis

In this systematic review, 12 articles were selected, almost the minimum sample number preferred for the funnel plot method. However, according to reports, funnel plots with small sample sizes can also reflect publication bias [24]. Based on Figs. 5 and 6, the publication bias results demonstrated a symmetrical distribution, indicating a minimal publication bias probability.

### Sensitivity assessment

The meta-analysis recorded insignificant alterations in each category after the type of analysis was adjusted, the effect size was modified, and individual articles were removed. Therefore, the sensitivity analysis verified the reliability of the findings.

## Discussion

The results indicate that exercise can improve the balance and executive function of children with ASD. Although heterogeneity is low ($I^2 = 37\% < 50\%$), further analysis is necessary to clarify the impact of intervention measures on heterogeneity. Meanwhile, through exploration of multiple factors, it was found that the duration of intervention may be an important factor affecting the heterogeneity of results. A previous study involving 19 tissues and 25 molecular platforms showed that many

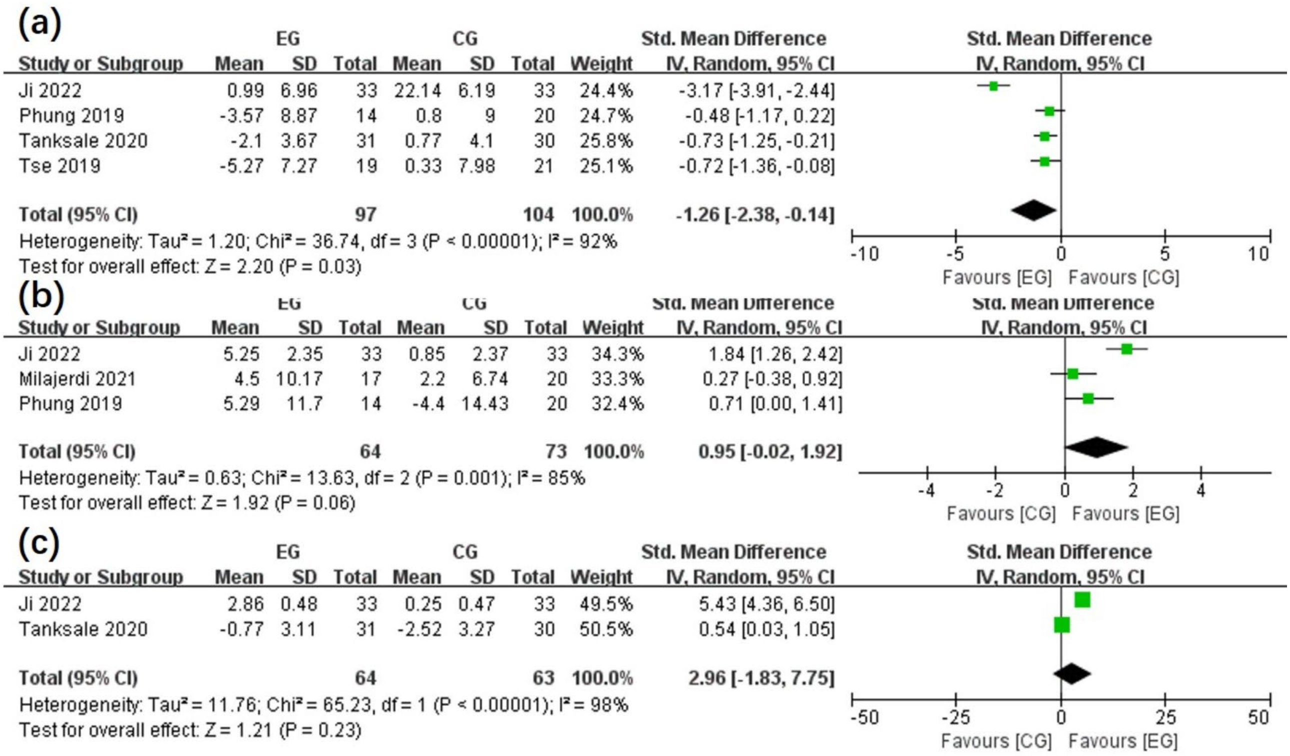


**Fig. 4** Forest plot portraying the effects of EG vs. CG intervention on the behavioural inhibition, flexibility and working memory

of the exercise-induced adaptive molecular changes do not emerge until 8 weeks after the exercise intervention [25]. Therefore, we conducted subgroup analysis with an intervention time of 8 weeks as the dividing point, and the results showed that exercise training beyond 8 weeks can improve balance, while shorter periods of time can reduce effectiveness. The discovery provided a critical value of the dose-response relationship for enhancing the balance function in children with ASD through exercise. Consequently, considering the effects of intervention duration on exercise effectiveness is vital when formulating exercise prescriptions and conducting research.

Balance management integrates three primary sensory inputs: visual, vestibular, and somatosensory systems [26]. Children suffering from motor dysfunction and disrupted balance are more vulnerable to falls during daily activities and may face escalated impairment in communication and interaction skills development [27]. The results of this review and previous analyses [12, 19] indicated that exercise training of over eight weeks enhanced balance in children with ASD.

In an investigation conducted by Ansari et al. [19], 20 children ASD patients were prescribed 10 weeks of aquatic exercises. The regime was performed twice weekly for 60 min each session. The children in the study had orientation and basic and free swimming training. According to the results, the intervention was conducive to enhancing the children's ability to maintain static and dynamic balance. In another study, Arslan et al. [12] employed structured circular training, totalling 12 weeks for three times a week. The program primarily included balance, strength, and jumping training. The report evaluated the ability of children with ASD to maintain balance on a balance beam. The EG recorded improved standing time compared to the CG, supporting the conclusion of this review.

Numerous exercise-based interventions [7, 19] were reportedly effective in improving balance in children with ASD. Nevertheless, determining the optimal intervention parameters was challenging due to inconsistent intervention plans and varied exercises applied. The outcomes of this meta-analysis revealed that only physical training performed over eight weeks had significant positive effects. The observation might be attributable to body function improvement through exercise requiring long-term accumulation. As such, physical training under eight weeks was not effective.

The mechanisms behind exercises in enhancing balance in children with ASD have not been fully understood. Nevertheless, evidence suggests that improved balance is related to visual, vestibular, and proprioceptive sense alterations [28]. Postural sway during sensory stimulations increases due to sensory stimuli changes [29, 30] arising from balance system adjustments to retain an upright posture [31]. In addition, structural changes in the brains of children with ASD may lead to many subtle

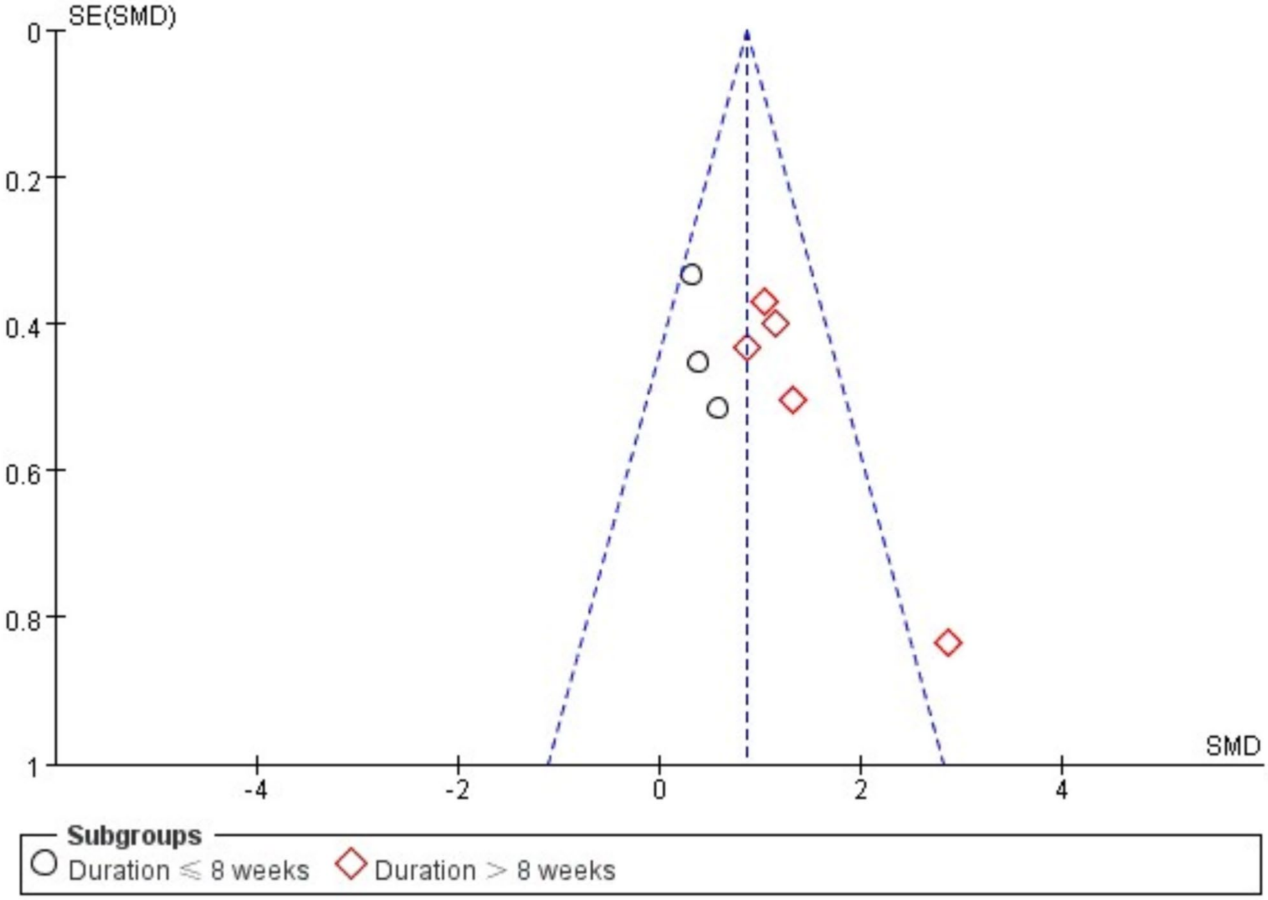


**Fig. 5** Funnel plot of publication bias in the EG vs. CG intervention for the balance

deficiencies in motor control, including postural instability, which may ultimately interfere with balance and cognitive development. The improvement of neuroplasticity through exercise may also be one of the mechanisms [32]. Exercise rehabilitation may improve early signs of central nervous system abnormalities, thereby enhancing behavioral inhibition and balance function [33].

Children with ASD have modulating sensory data issues and visual processing deficiencies [34, 35]. Consequently, postural sway in children with ASD rose with visual information unavailability [36]. Stins et al. [27] also reported that children suffering from mild ASD had increased postural instability in the mediolateral direction while their eyes were closed. The data suggested that ASD patients had enhanced dependency on visual input to regulate balance, rendering balance maintenance challenging [27].

Based on autism-related complications and considering the importance of sensory integration signals for maintaining balance in patients of ASD, physical activity interventions could be among the most advantageous and regulatory approaches to minimise balance deficit [37]. Furthermore, relevant reports have noted that muscles are receptors in the central nervous system of the brain. The muscles receive the information mentioned above before providing feedback. Muscle strength also directly affects whether the body can ultimately maintain internal balance [38]. Body flexibility and balance are intimately associated. Improving flexibility can enhance coordination and balance, which are critical for posture control [39]. Exercise is a vital step to enhance muscle strength and body flexibility. As such, physical training might also improve the balance of children with ASD by increasing lower limb muscle strength and flexibility.

BI, WM and FL all fall under the umbrella of executive function. The results of this study show the positive effects of a motor intervention on BI. This is similar to the results of a previous study in which 40 children with ASD in the study by Tse et al. [23] utilized a basketball skill acquisition intervention for 45 min twice a week for 12 weeks. The Go/No-Go test was utilized to assess participants' BI. The results showed that the exercise group was more effective in improving the level of BI in children with ASD compared to the control group. One possible explanation for the executive function benefits relates to the neurotrophic hypothesis [40–42]. According to

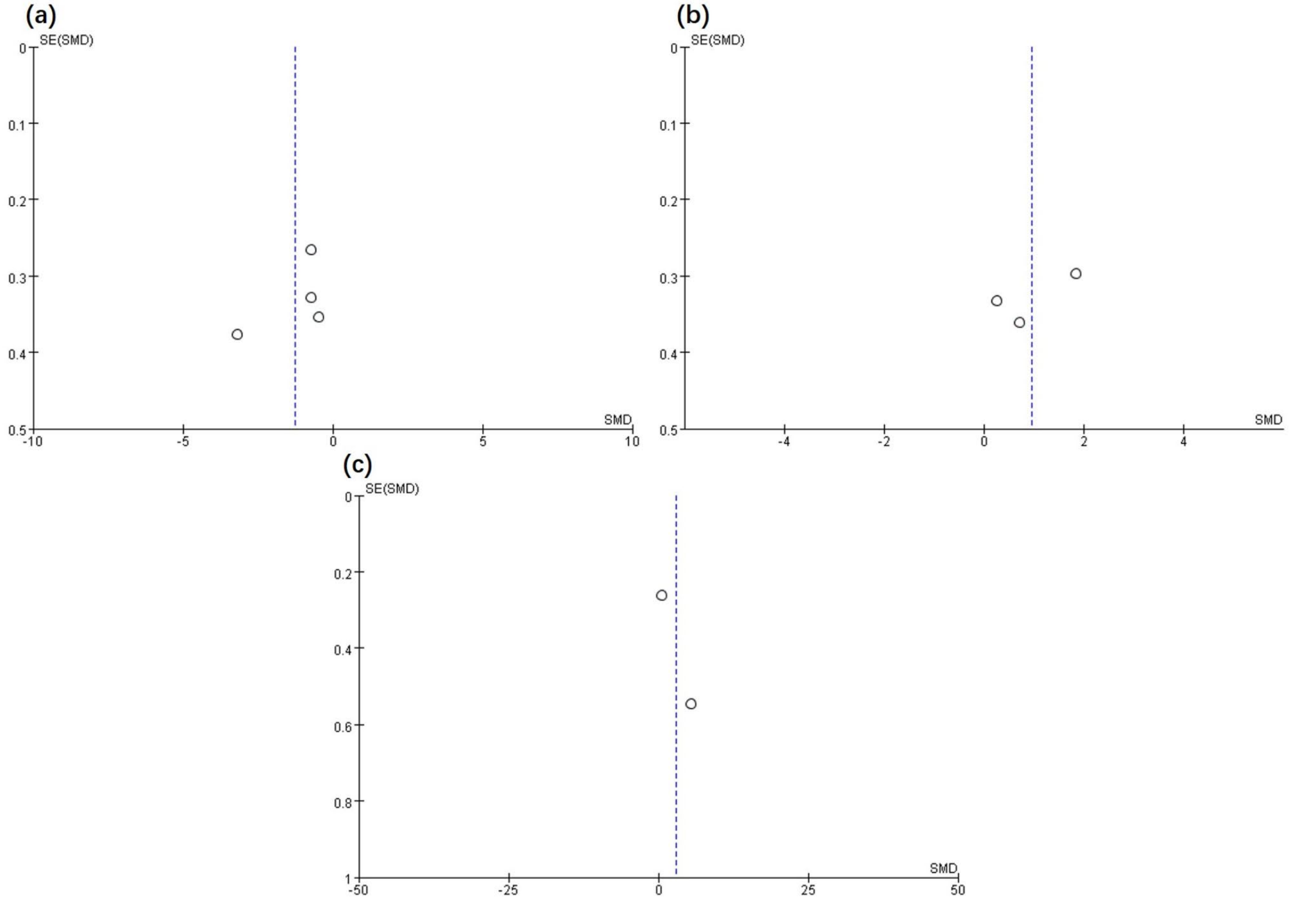


**Fig. 6** Funnel plot of publication bias in the EG vs. CG intervention for the behavioural inhibition, flexibility and working memory

this hypothesis, physical activity increases metabolic demand and triggers a series of biochemical changes, such as enhanced cerebral blood flow and increased levels of brain-derived neurotrophic factors, which in turn enhances the brain's plasticity for high-level cognitive activity and subsequently improves executive function [43].

This review has several shortcomings. Firstly, the number of included articles was relatively small, which might not accurately represent the intervention effects on the entire population. This meta-analysis of RCT investigations also included trials involving different ages, statistical and evaluation methods, and exercise intervention details. These differences may limit accurate horizontal comparisons between studies. As such, future reviews can consider incorporating more publications to enhance the credibility of the results. More diverse intervention programs can also be considered, such as transcranial electrical stimulation, cognitive training, and more. Furthermore, more physiological or psychological indicators, such as brain-derived neurotrophic factor, inflammation, anxiety, depression, and sleep status, can be incorporated as research continues. Finally, determining precise dose-response relationships to effectively enhance the balance and executive function of children with ASD would be beneficial.

## Conclusion

Exercise interventions can better improve the balance and behavioural inhibition of children with ASD compared to CG. Nevertheless, physical training prescribed for more than eight weeks led to a more significant improvement in balance than interventions performed for shorter periods. It is recommended that clinicians and educators working with children with autism spectrum disorders should be mindful of the impact of intervention duration on intervention outcomes when developing exercise programs, and should try to engage participants in intervention programs of more than 8 weeks.

## Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s13102-025-01142-1.

Supplementary Material 1

Supplementary Material 2

Supplementary Material 3

Supplementary Material 4

**Acknowledgements**
Not Applicable.

**Author contributions**
Haixia Li wrote the main manuscript text. Haixia Li prepared Figs. 1, 2, 3, 4, 5 and 6; Table 1. Ruiyun Zhang drafted and reviewed the manuscript.

**Funding**
Not Applicable.

**Data availability**
If necessary, it can be obtained from the corresponding author.

## Declarations

**Ethics approval and consent to participate**
Not Applicable.

**Consent for publication**
Not Applicable.

**Competing interests**
The authors declare no competing interests.

Received: 31 January 2025 / Accepted: 1 April 2025

### References

1. Lord C, Elsabbagh M, Baird G, Veenstra-Vanderweele J. Autism spectrum disorder. Lancet (London England). 2018;392(10146):508–20. https://doi.org/10.1016/S0140-6736(18)31129-2
2. Sapey-Triomphe LA, Lamberton F, Sonié S, Mattout J, Schmitz C. Tactile hypersensitivity and GABA concentration in the sensorimotor cortex of adults with autism. Autism Res. 2019;12(4):562–75. https://doi.org/10.1002/aur.2073
3. Travers BG, Mason A, Gruben KG, Dean DC, McLaughlin K. Standing balance on unsteady surfaces in children on the autism spectrum: the effects of IQ. Res Autism Spectr Disord. 2018;51:9–17. https://doi.org/10.1016/j.rasd.2018.03.008
4. Lim YH, Partridge K, Girdler S, Morris SL. Standing postural control in individuals with autism spectrum disorder: systematic review and meta-analysis. J Autism Dev Disord. 2017;47(7):2238–53. https://doi.org/10.1007/s10803-017-3144-y
5. Minshew NJ, Sung K, Jones BL, Furman JM. Underdevelopment of the postural control system in autism. Neurology. 2004;63(11):2056–61. https://doi.org/10.1212/01.wnl.0000145771.98657.62
6. Rafiei Milajerdi H, Sheikh M, Najafabadi MG, Saghaei B, Naghdi N, Dewey D. The effects of physical activity and exergaming on motor skills and executive functions in children with autism spectrum disorder. Games Health J. 2021;10(1):33–42. https://doi.org/10.1089/g4h.2019.0180
7. Djordjević M, Memisevic H, Potic S, Djuric U. Exercise-based interventions aimed at improving balance in children with autism spectrum disorder: a meta-analysis. Percept Mot Skills. 2022;129(1):90–119. https://doi.org/10.1177/00315125211060231
8. Pan CY, Chu CH, Tsai CL, Sung MC, Huang CY, Ma WY. The impacts of physical activity intervention on physical and cognitive outcomes in children with autism spectrum disorder. Autism. 2017;21(2):190–202. https://doi.org/10.1177/1362361316633562
9. Hassani F, Shahrbanian S, Shahidi SH, Sheikh M. Playing games can improve physical performance in children with autism. Int J Dev Disabil. 2022;68(2):219–26. https://doi.org/10.1080/20473869.2020.1752995
10. Roșca AM, Rusu L, Marin MI, Ene Voiculescu V, Ene Voiculescu C. Physical activity design for balance rehabilitation in children with autism spectrum disorder. Child (Basel Switzerland). 2022;9(8). https://doi.org/10.3390/children9081152
11. Ben Hassen I, Abid R, Ben Waer F, et al. Intervention based on psychomotor rehabilitation in children with autism spectrum disorder ASD: effect on postural control and sensory integration. Child (Basel Switzerland). 2023;10(9). https://doi.org/10.3390/children10091480
12. Arslan E, Ince G, Akyüz M. Effects of a 12-week structured circuit exercise program on physical fitness levels of children with autism spectrum condition and typically developing children. Int J Dev Disabil. 2022;68(4):500–10. https://doi.org/10.1080/20473869.2020.1819943
13. Higgins JPT, Thomas J, Chandler J, et al. In: Higgins JPT, Thomas J, Chandler J, et al. editors. Cochrane handbook for systematic reviews of interventions. Wiley; 2019. https://doi.org/10.1002/9781119536604
14. Li S, Shaharudin S, Cirer-Sastre R, Li F, Abdul Manaf F, Mohd Shukri MF. Effects of high-intensity interval exercise on cardiac troponin elevation when comparing with moderate-intensity continuous exercise: a systematic review and meta-analysis. PeerJ. 2023;11:e14508. https://doi.org/10.7717/peerj.14508
15. Hatipoğlu Özcan G, Özer DF, Pınar S. Effects of motor intervention program on academic skills, motor skills and social skills in children with autism spectrum disorder. J Autism Dev Disord Published Online May. 2024;16. https://doi.org/10.1007/s10803-024-06384-5
16. Haghighi AH, Broughani S, Askari R, Shahrabadi H, Souza D, Gentil P. Combined physical training strategies improve physical fitness, behavior, and social skills of autistic children. J Autism Dev Disord. 2023;53(11):4271–9. https://doi.org/10.1007/s10803-022-05731-8
17. Draudvilienė L, Draudvila J, Stankevičiūtė S, Daniusevičiūtė-Brazaitė L. Two physiotherapy methods to improve the physical condition of children with autism spectrum disorder. Child (Basel Switzerland). 2024;11(7). https://doi.org/10.3390/children11070798
18. Bo J, Shen B, Pang Y, et al. Transfer and retention effects of a motor program in children with autism spectrum disorders. Adapt Phys Activ Q. 2024;41(1):88–106. https://doi.org/10.1123/apaq.2022-0200
19. Ansari S, Hosseinkhanzadeh AA, AdibSaber F, Shojaei M, Daneshfar A. The effects of aquatic versus kata techniques training on static and dynamic balance in children with autism spectrum disorder. J Autism Dev Disord. 2021;51(9):3180–6. https://doi.org/10.1007/s10803-020-04785-w
20. Ji C, Yang J, Lin L, Chen S. Executive function improvement for children with autism spectrum disorder: a comparative study between virtual training and physical exercise methods. Child (Basel Switzerland). 2022;9(4). https://doi.org/10.3390/children9040507
21. Phung JN, Goldberg WA. Promoting executive functioning in children with autism spectrum disorder through mixed martial arts training. J Autism Dev Disord. 2019;49(9):3669–84. https://doi.org/10.1007/s10803-019-04072-3
22. Tanksale R, Sofronoff K, Sheffield J, Gilmour J. Evaluating the effects of a yoga-based program integrated with third-wave cognitive behavioral therapy components on self-regulation in children on the autism spectrum: a pilot randomized controlled trial. Autism. 2021;25(4):995–1008. https://doi.org/10.1177/1362361320974841
23. Tse CYA, Lee HP, Chan KSK, Edgar VB, Wilkinson-Smith A, Lai WHE. Examining the impact of physical activity on sleep quality and executive functions in children with autism spectrum disorder: a randomized controlled trial. Autism. 2019;23(7):1699–710. https://doi.org/10.1177/1362361318823910
24. Lu Y, Wang W, Ding X, Shi X. Association between the promoter region of serotonin transporter polymorphisms and recurrent aphthous stomatitis: a meta-analysis. Arch Oral Biol. 2020;109:104555. https://doi.org/10.1016/j.archoralbio.2019.104555
25. MoTrPAC Study Group, Analysts L, MoTrPAC Study Group. Temporal dynamics of the multi-omic response to endurance exercise training. Nature. 2024;629(8010):174–83. https://doi.org/10.1038/s41586-023-06877-w
26. Cordo PJ, Nashner LM. Properties of postural adjustments associated with rapid arm movements. J Neurophysiol. 1982;47(2):287–302. https://doi.org/10.1152/jn.1982.47.2.287
27. Stins JF, Emck C, de Vries EM, Doop S, Beek PJ. Attentional and sensory contributions to postural sway in children with autism spectrum disorder. Gait Posture. 2015;42(2):199–203. https://doi.org/10.1016/j.gaitpost.2015.05.010
28. Sienko KH, Seidler RD, Carender WJ, Goodworth AD, Whitney SL, Peterka RJ. Potential mechanisms of sensory augmentation systems on human balance control. Front Neurol. 2018;9:944. https://doi.org/10.3389/fneur.2018.00944
29. Li T, Zhang C, Wang X, Zhang X, Wu Z, Liang Y. The impact of stroboscopic visual conditions on the performance of elite curling athletes. Life (Basel Switzerland). 2024;14(9). https://doi.org/10.3390/life14091184
30. Assländer L, Peterka RJ. Sensory reweighting dynamics in human postural control. J Neurophysiol. 2014;111(9):1852–64. https://doi.org/10.1152/jn.00669.2013

31. Carver S, Kiemel T, Jeka JJ. Modeling the dynamics of sensory reweighting. Biol Cybern. 2006;95(2):123–34. https://doi.org/10.1007/s00422-006-0069-5
32. Rogge AK, Röder B, Zech A, Hötting K. Exercise-induced neuroplasticity: balance training increases cortical thickness in visual and vestibular cortical regions. NeuroImage. 2018;179:471–9. https://doi.org/10.1016/j.neuroimage.2018.06.065
33. Sato M, Betriana F, Tanioka R, Osaka K, Tanioka T, Schoenhofer S. Balance of autonomic nervous activity, exercise, and sleep status in older adults: a review of the literature. Int J Environ Res Public Health. 2021;18(24). https://doi.org/10.3390/ijerph182412896
34. Gowen E, Hamilton A. Motor abilities in autism: a review using a computational context. J Autism Dev Disord. 2013;43(2):323–44. https://doi.org/10.1007/s10803-012-1574-0
35. Ben-Sasson A, Hen L, Fluss R, Cermak SA, Engel-Yeger B, Gal E. A meta-analysis of sensory modulation symptoms in individuals with autism spectrum disorders. J Autism Dev Disord. 2009;39(1):1–11. https://doi.org/10.1007/s10803-008-0593-3
36. Fears NE, Sherrod GMC, Templin TN, Bugnariu NL, Patterson RM, Miller HL. Community-based postural control assessment in autistic individuals indicates a similar but delayed trajectory compared to neurotypical individuals. Autism Res. 2023;16(3):543–57. https://doi.org/10.1002/aur.2889
37. Cheldavi H, Shakerian S, Shetab Boshehri SN, Zarghami M. The effects of balance training intervention on postural control of children with autism spectrum disorder: role of sensory information. Res Autism Spectr Disord. 2014;8(1):8–14. https://doi.org/10.1016/j.rasd.2013.09.016
38. Leroux A, Pinet H, Nadeau S. Task-oriented intervention in chronic stroke: changes in clinical and laboratory measures of balance and mobility. Am J Phys Med Rehabil. 2006;85(10):820–30. https://doi.org/10.1097/01.phm.0000233179.64769.8c
39. Seco J, Abecia LC, Echevarría E, et al. A long-term physical activity training program increases strength and flexibility, and improves balance in older adults. Rehabil Nurs. 2013;38(1):37–47. https://doi.org/10.1002/rnj.64
40. Mazaheri A, Tarkhan A, Mirakhori F. The impact of virtual reality games on reducing motor and cognitive disorders in children with autism spectrum: a meta-analytical review. AI Tech Behav Soc Sci. 2024;2(1):25–34. https://doi.org/10.61838/kman.aitech.2.1.4
41. Zourmand G, Pavlović R, Taheri M. The effect of school games on motor skills development in children with autism. Ann Appl Sport Sci. 2024;12(Spring Supplementary):0–0. https://doi.org/10.61186/aassjournal.1294
42. Khan NA, Hillman CH. The relation of childhood physical activity and aerobic fitness to brain function and cognition: a review. Pediatr Exerc Sci. 2014;26(2):138–46. https://doi.org/10.1123/pes.2013-0125
43. Farrukh S, Habib S, Rafaqat A, Sarfraz A, Sarfraz Z, Tariq H. Association of exercise, brain-derived neurotrophic factor, and cognition among older women: a systematic review and meta-analysis. Arch Gerontol Geriatr. 2023;114:105068. https://doi.org/10.1016/j.archger.2023.105068

## Publisher's note