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Network meta-analysis of the effects of different exercise therapies on autism spectrum disorder

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Abstract: *The incidence of autism spectrum disorders (ASD) is increasing year by year, placing a huge economic and emotional burden on society and families. Exercise is an effective behavioural intervention. The aim of this study was to explore the effects of different exercise modalities on the abnormal behavioural performance of ASD.A network meta-analysis of published studies related to exercise interventions for ASD was performed by searching PubMed, Cochrane Library, Web of Science, EBSCO, CNKI, Wanfang, and VIP database with a time period up to July 2024. A total of 63 studies were considered eligible for inclusion, including 2,231 patients with ASD. According to the SUCRA ranking, it can be inferred that sports games (70.9), horseback riding therapy (84.8) are more effective in alleviating the severity of autism and social communication deficits in ASD. Exercise can effectively improve social adaptability, motor skills, static balance, sensory abnormalities, emotional problems, quality of life, and executive function. The meta-analysis results showed that the effect of ASD exercise intervention for more than 12 weeks was significantly higher than that for less than 12 weeks. In cycles of more than 12 weeks, the frequency of more than 3 times per week is significantly higher than that of less than 3 times, with each session lasting more than 60 minutes but higher than that of less than 60 minutes. Sports games, horseback riding are the optimal choices for ASD physical activity interventions. The best dosage for ASD exercise intervention involves interventions lasting over 12 weeks, with sessions at least three times per week, each lasting 60 minutes or longer.*

Keywords: *Autism Spectrum Disorder, Exercise Therapy, Network Meta-Analysis, Core Symptoms, Children, Adolescents*

1. Introduction

Autism spectrum disorder (ASD) is a common, highly heritable, and heterogeneous neurodevelopmental disorder, encompassing conditions such as autism, Asperger syndrome, and pervasive developmental disorder. These disorders are characterized by underlying cognitive characteristics and frequently co-occur with other conditions[1]. The core symptoms of ASD include social communication deficits and repetitive patterns of behavior, interests, or activities, often accompanied by motor skill deficits, and emotional difficulties[2]. The etiology of ASD is complex and not yet fully understood, involving a combination of genetic and environmental factors[3].

The prevalence of ASD is increasing every year, with the World Health Organization (WHO) estimating a global prevalence of 0.76%[4]. In 2023, the Centers for Disease Control and Prevention (CDC) reported a prevalence rate of 1 in 36 among 8-year-olds in the United States[5]. In China, epidemiological studies indicate that the prevalence of ASD among school-aged children (6-12 years) is 0.7%, suggesting that nearly 700,000 children in China are affected by ASD[6]. The increasing incidence of ASD, with its early and often lifelong onset, places an enormous economic and emotional burden on families and society. Currently, there are no specific pharmacological treatments for ASD, with medications such as risperidone and aripiprazole being used primarily for symptom management. As a result, ASD interventions rely primarily on nonpharmacological approaches, including Applied Behavior Analysis (ABA), the Denver Early Start Model, sensory integration therapy, the TEACCH system, and exercise interventions, which form an essential component of the overall treatment strategy[7]. Most behavioral intervention models require specific environmental settings, while exercise interventions offer the advantage of greater convenience. In addition, physical activity interventions are cost-effective, easy to

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implement, and less likely to cause adverse effects, making them an area of increasing interest.

In the 1970s, evidence emerged for the positive impact of physical exercise on stereotyped behaviors in children with ASD[8]. As research advances, exercise interventions are increasingly being integrated into the treatment of ASD. A substantial body of experimental evidence supports the effectiveness of exercise in alleviating social communication deficits and repetitive behaviors in both ASD animal models and patients[9, 10]. Studies have confirmed that exercise can enhance brain plasticity in ASD patients, including improvements in white matter integrity and gray matter volume, ultimately leading to reductions in autism-like behaviors[11]. Exercise interventions can rapidly modulate central and peripheral neurotransmitter levels, signaling molecules, and neurotrophic factors, which in turn facilitate neuronal structural connectivity and functional reorganization. These neurobiological changes positively affect social functioning[12]. Consequently, these processes contribute to improvements in social and cognitive skills in children with ASD[13]. However, not all studies have reported that exercise alleviates abnormal behaviors in individuals with ASD. Some research has shown that regular physical activity does not significantly alter the atypical behaviors observed in ASD patients[14]. This discrepancy can be attributed to autism heterogeneity and variations in the intervention methods employed.

Currently, a variety of physical intervention methods are commonly employed in the treatment of autism, including equine-assisted therapy, martial arts, swimming, yoga/dance, sports games and so on.[15]. The duration of interventions typically ranges between 12 and 18 weeks on average. The challenge in determining the superiority of different interventions lies in the variety of available programs and the lack of direct evidence comparing them. As a result, selecting the most effective intervention strategy remains difficult. To identify the most suitable type of physical activity for improving health outcomes related to ASD, it is necessary to employ a Network meta-analysis (NMA). NMA enables the comparison of different interventions by integrating data from both direct comparisons and indirect comparisons across a network of treatments, thereby assessing the relative advantages of various interventions[16]. This study aims to use NMA to assess the effects of various exercise interventions on the severity of autism and social communication deficits in individuals with ASD. The goal is to determine the optimal exercise intervention and duration. In addition, traditional meta-analysis will be used to explore the impact of exercise on stereotyped behaviours, motor skills development, quality of life, emotional problems, sensory abnormalities, social adaptability, and executive function. This comprehensive analysis seeks to assess the overall effectiveness of exercise interventions in ASD patients and identify the most effective intervention strategies and durations. The findings aim to provide evidence and data to support the development of exercise prescriptions for clinicians in the future.

2. Data and methods

NMA is performed according to the preferred reporting items in the System Review and meta-analysis (PRISMA) guide[17]. (PROSPERO: CRD42024578887).

2.1 Search procedures

The literature search was performed for the related research studies, mainly from the following databases: PubMed, Cochrane Library, Web of Science, EBSCO, CNKI, Wanfang, and VIP database. The search keywords we used were [(exercise intervention OR sport intervention) AND (ASD OR autism OR Autism spectrum disorder) AND (RCTs OR random OR randomized controlled trial)],[(Wrestling OR boxing OR pugilism OR horseback riding OR football OR soccer OR basketball OR yoga OR jogging OR rhythmic gymnastics OR swimming OR aquatics OR ping pang OR martial arts OR sports games OR cycling OR strength training OR taekwondo OR Tai Chi OR Wrestling) AND (ASD OR autism OR Autism spectrum disorder) AND (RCTs OR random OR randomized controlled trial)]. The retrieval time is limited to July 2024.

2.2 Inclusion criteria and exclusion criteria

The inclusion criteria for this study were as follows: (1) The intervention consisted solely of exercise, with no pharmacological treatments involved; (2) Participants were diagnosed with ASD; (3) There were no significant differences in baseline characteristics between groups prior to the intervention; (4) Data were available; (5) The outcome measures include the degree of autism or social disorders, stereotyped behavior or emotional disorders, sensory abnormalities, dynamic or static balance, quality of life, or executive function. Studies were excluded based on the following criteria: (1) Inability to obtain precise

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data; (2) Animal experiments, abstracts, case reports, reviews, systematic reviews, or duplicate publications; (3) Combined interventions involving exercise and medication or other methods;(4) Participants with additional conditions such as ADHD.

2.3 Data extraction

Two authors independently screened abstracts and full-text articles from the selected studies, extracted data, and performed cross-verification. In cases of disagreement, a third party was consulted to mediate and reach consensus. During the literature screening process, titles and abstracts were initially reviewed, followed by a full-text review to determine the exclusion of ineligible studies.

2.4 Quality assessment

Two researchers independently conducted a literature quality assessment. And the disagreement was resolved with the assistance of a third researcher. The methodological quality of the included studies was assessed using the Physiotherapy Evidence Database (PEDro) scale (https://pedro.org.au/simplified-chinese/resources/pedro-scale/), which consists of 11 evaluation items. Studies scoring 0–3 were classified as low-quality, 4–7 as moderate-quality, and 8–11 as high-quality[18].

2.5 Statistical analysis

For the outcome measures associated with intervention programs, a multivariate network meta-analysis was conducted within a frequentist framework using the "mvmeta" command in STATA (Version 17.0). The therapeutic effects of each study on ASD were quantified using standardized mean difference (SMD) and standard deviation (SD). A meta-analysis of all included studies was performed in STATA 17.0 for discrete outcome measures of intervention programs, followed by Egger's test to assess publication bias. Heterogeneity was assessed using the I^2 statistic, with values exceeding 50% indicating substantial heterogeneity. Consistency was assessed by comparing treatment effects estimated from direct comparisons with those estimated from indirect comparisons.

3. Result

3.1 Literature selection

Initially, 3620 studies were identified. 63 studies were deemed eligible for inclusion. Of these, 24 studies were Chinese and 39studies in English (Figure 1).

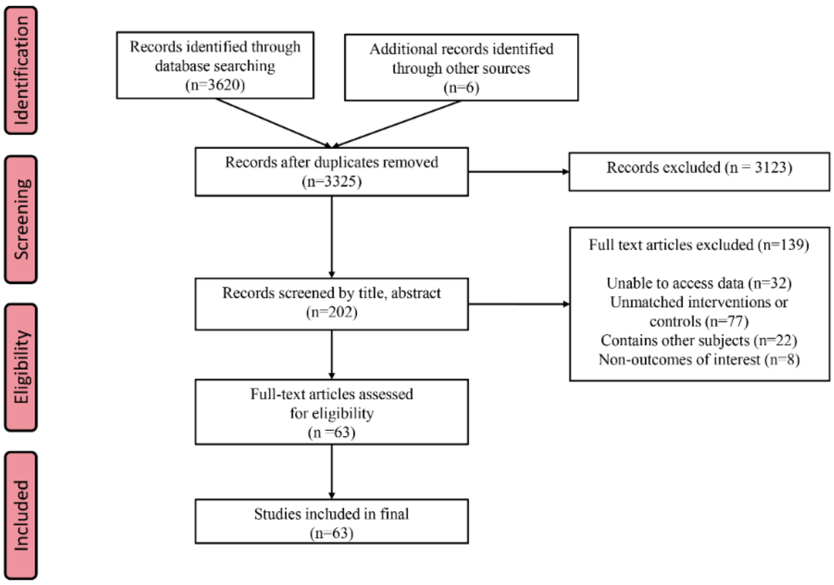

Figure1: Flow diagram for studies included in and excluded from meta-analysis.

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3.2 Characteristics of the included studies

A total of 63 studies were included, including 2,231 ASD patients, with 1,108 in the control group and 1,123 in the intervention group (Table1).

Table 1 Characteristics of the included studies.

No.	Study	Participates			Intervention Program	Physical Activity Intervention			Outcomes	PEDor
		Sample Size(n)	Age	Diagnosis		Frequency	Time (min)	Duration (week)		
1	Yang [19], 2024	30(CG:15, EG:15)	3-6	DSM-V	CG:None EG:Ball games	5	40	12	SRS-2, CARS, CSHQ	9
2	Xing[20], 2024	17(CG:8, EG:9)	3-6	Hospital diagnosis	CG:None EG:yoga	3	45-50	8	ABC, MABC-2	9
3	Dong[21], 2023	58(CG:26, EG:32)	6.4± 2.07	DSM-V	CG:None EG:Mini basketball	5	40	12	SRS-2, RBS-R	7
4	Sindhu[22], 2023	43(CG:20, EG:23)	5-15	Hospital diagnosis	CG:None EG:yoga	1	40	12	SRS-2, ABC-2	7
5	Yu-Ru[23], 2023	13(CG:6, EG:7)	4-6	DSM-V	CG:None EG:Adaptive sports activities	1	90	6	CARS2, TONI–4, MABC-2	8
6	Roza[24], 2022	23(CG:11, EG:12)	9.6± 1.4	Hospital diagnosis	CG:None EG:Mind-body exercise	3	45	12	Gliam	7
7	Fahimeh[25], 2022	30(CG:15, EG:15)	8-11	DSM-V	CG:None EG:Sports games	1	90	24	BOT	8
8	Marie[26], 2022	24(CG:12, EG:12)	5-18	GARS	CG:None EG:Adaptive sports activities	3	60	16	ASC-ASD	7
9	CHIEN[27],2 010	16(CG:8, EG:8)	6-9	DSM-V	CG:None EG:Aquatic exercise	2	90	10	SSBS2	8
10	Wuang[28], 2010	60(CG:30, EG:30)	6-10	DSM-IV	CG:None EG:Horseback riding	2	60	20	BOTMP, TSIF	9
11	Fatimah,[29] 2012	30(CG:15, EG:15)	5-16	DSM-IV	CG:None EG:Karate	4	30-90	14	SSGARS-2	7
12	Agnes[14],20 13	40(CG:20, EG:20)	6-17	DSM-IV	CG:None EG1:Mind-body exercise	2	20	4	ATEC	8
13	Ahmadreza[30],2013	30(CG:15, EG:15)	5-16	DSM-IV	CG:None EG:Karate	4	30-90	14	SSGARS-2	7
14	Fatimah[31], 2016	30(CG:15, EG:15)	5-16	DSM-IV	CG:None EG:Karate	4	30-90	14	CSGARS-2	7
15	Marta[32],20 16	27(CG:14, EG:13)	6-12	DSM-IV	CG:None EG:Horseback riding	1	60-70	24	VABS	8
16	Yumi[33],20 16	14(CG:8, EG:6)	8-10	DSM-IV	CG: None EG:Karate	2	50	8	Balance ability	6
17	Soleyman[34],2021	20(CG:10, EG:10)	8-14	DSM-v	CG: None EG: Aquatic exercise EG2: Karate	2	60	10	Balance ability	7
18	Forouzan[35],2017	20(CG:10, EG:10)	9-12	DSM-IV	CG:None EG:Karate	3	45	10	BOTMP	8
19	Giovanni[36],2018	26(CG:13, EG:13)	8.3± 2.3	DSM-IV	CG:None EG:Aquatic exercise	2	45	40	CARS, VABS	8
20	Mahboubeh [37],2018	26(CG:14, EG:12)	5-12	DSM-IV	CG:None EG:Sports games	3	40	12	GARS-2, ATEC	8
21	Pan[38],2018	14(CG:7, EG:7)	6-16	ABC-C ADOS-2	CG:None EG:Aquatic exercise	1	45	10	ABC-C	8
22	Andy C[39],2020	27(CG:12, EG:15)	8-12	DSM-V	CG:None EG:Sports games	4	30	12	CBCL	7
23	Margaret[40],2009	34(CG:15, EG:19)	6.95± 1.67	DSM-IV	CG: None EG: Horseback riding	1	60	12	SRS	7
24	Robin L.[41],2015	97(CG:47, EG:50)	6-16	SCQ, ADOS-2	CG:None EG:Jogging	1	45	10	ABC, SRS, BOT2, VABS	9
25	Mostafa[42], 2019	18(CG:9, EG:9)	3-8	DSM-V	CG: None EG: Mind-body exercise	3	60	6	MABC-2	8
26	Marzouki et al. [43](2022)	14(CG:6, EG:8)	5-18	GARS	CG: None EG: Horseback riding	2	50	8	GARS-2	7
27	Phung et al.[44] (2021)	34(CG:20, EG:14)	8-11	ADOS-2	CG:None EG:Mind-body exercise	2	45	13	SSIS	7
28	Wang et al. [45](2020)	33(CG:15, EG:18)	3-6	DSM-V	CG:None EG:Aquatic exercise	5	40	12	SRS-2, RBS-R	6
29	Cai et al. [11](2020)	29(CG:14, EG:15)	3-6	DSM-V	CG:None EG:Mind-body exercise	5	40	12	SRS-2	6
30	Cai et al.[46] (2020)	30(CG:15, EG:15)	3-6	DSM-V	CG:None EG:Ball games	5	40	12	SRS-2	7
31	Hildebrandt	75(CG:22,	14-65	DSM-V	CG:None	NR	60	10	SANS	9

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	et al.[47], (2016)	EG:53)			EG:Ball games					
32	Zanobini et al. [48](2019)	25(CG:12, EG:13)	3-8	DSM-V	CG:None EG:Ball games	0.5	30	24	SRS, ABC	6
33	Koch et al. [49](2015)	31(CG:15, EG:16)	22± 7.7	ICD-10	CG:None EG:Rhythmic gymnastics	Nr	60	7	FBT	6
34	Yang et al. [50],(2021)	30(CG:15, EG:15)	3-6	DSM-v	CG:None EG:Ball games	5	40	12	SRS-2	6
35	Aithal et al. [51](2021)	26(CG:16, EG:10)	<16	DSM-v	CG:None EG:Rhythmic gymnastics	2	40	5	SCQ	8
36	Amir et al.[52]2023	16(CG:8, EG:8)	6-10	GARS2	CG:None EG:Adaptive sports activities	3	60-80	8	GARS-2	10
37	Androulla [53], 2017	24 (CG:14, EG:10)	7.5± 10.57	GARS	CG: None EG:Horseback riding	5-7	45	7	CARS-2	6
38	Wang [54], 2024	16(CG:8, EG:8)	7-10	DSM-V	CG:None EG:Rhythmic gymnastics	3	60	8	TGMD-3	6
39	Meng [55], 2024	60(CG:30, EG:30)	4-12	DSM-V	CG:None EG:Sports games	2	60	10	ABC, C-PEP	8
40	Liu[56], 2024	72(CG:36, EG:36)	4-6	DSM-V	CG:None EG:Sports games	2	60	12	SRS, peds-ql 4.0	9
41	Li[57], 2024	21(CG:8, EG:13)	>5	DSM-V	CG:None EG:Jumping rope	5	60	10	CHEXI	6
42	Wang [58], 2023	48(CG:24, EG:24)	4.54± 1.02	DSM-V	CG: None EG:Sports games	5	120	24	PEP - 3	7
43	Shang[59], 2023	59(CG:19, EG:40)	7.17± 1.98	DSM-V	CG:None EG:Sports games	1	None	56	ABC	8
44	Sha [60], 2023	36(CG:18, EG:18)	10.39 ±2.4	DSM-V	CG:None EG:Ball games	2	60	16	SRS, ASSS	9
45	Luan [61],2023	16(CG:8, EG:8)	7-10	DSM-V	CG:None EG:Rhythmic gymnastics	3	60	8	ASSS	7
46	Geng [62], 2023	46(CG:23, EG:23)	3-7	DSM-V	CG:None EG:Adaptive sports activities	6	30	12	CARS, ABC	8
47	Fei [63], 2023	62(CG:31, EG:31)	2-6	DSM-V	CG:None EG:Adaptive sports activities	None	None	40	TGMD-3	8
48	Wang [64], 2022	30(CG:15, EG:15)	5-15	DSM-V	CG: None EG: Horseback riding	2-3	45-60	24	ATEC, SRS, CP-GMFQ	8
49	Liu [65], 2021	60(CG:30, EG:30)	0-6	DSM-V	CG:None EG:Sports games	1	None	24	CARS	7
50	Liu [66], 2021	23(CG:10, EG:13)	6-10	DSM-V	CG:None EG:Adaptive sports activities	4	60	6	CARS ABC, TGMD-3	7
51	Dong, [67]2021	18(CG:10, EG:8)	5-12	ADI-R	CG:None EG:Adaptive sports activities	3	60	12	SRS, ASSS	7
52	Song [68], 2020	92(CG:46, EG:46)	4-11	Hospital diagnosis	CG:None EG:Aquatic exercise	2-3	90	16	TGMD-3, POPE, C-PEP3	7
53	Dong [69], 2020	30(CG:15, EG:15)	3-6	DSM-V	CG:None EG:Ball games	5	40	12	ATEC, Peds-QL	8
54	Zhang[70], 2019	40(CG:20, EG:20)	3-6	GARS	CG:None EG:Mind-body exercise	7	45	24	CARS, CSHQ, CEBQ	9
55	Jiang [71], 2018	40(CG:10, EG1:10, EG2:10,EG 3:10)	12-18	Hospital diagnosis	CG:None EG1:Sports games EG2:Ball games EG3:Rhythmic gymnastics	1-3	60	24	ABC, CARS	7
56	Zhang[72], 2017	60(CG:30, EG:30)	3-11	DSM-V	CG:None EG:Sports games	7	None	24	ABC	8
57	Feng [73], 2017	40(CG:20, EG:20)	7.11+ 1.71	DSM-IV	CG:None EG:Aquatic exercise	5	90	4	CARS, CABS	8
58	Yang [74], 2016	80(CG:40, EG:40)	3-10	ICD-10	CG:None EG:Sports games	6	90	24	ABC, HAAR	7
59	Pei [75], 2014	16(CG:8, EG:8)	7-10	Hospital diagnosis	CG:None EG: Rhythmic gymnastics	5	30	12	CARS, ATEC	6
60	Wang [76], 2020	54(CG:26, EG:28)	7.36± 1.56	CCMD-3	CG: None EG: Aquatic exercise	1	60	8	SOT, MCT	6
61	Marzuki,[77] 2022	14 (CG:6, EG:8)	6.3± 0.5	DSM-V	CG:None EG:Aquatic exercise	2	50	8	CARS	6
62	Kristie,[78]2 012	46 (CG:22, EG:24)	5-12	DSM-V	CG: None EG: Yoga	7	15-20	16	ABC-C	5
63	Wu [79],	14 (CG:7, EG,7)	4-10	DSM-V	CG: None EG:Aquatic exercise	5	90	4	CARS	6

Note: CG: Control group, EG: Experiential group, DSM: Diagnostic and Statistical Manual of Mental Disorders, CARS: Childhood Autism Rating Scale, ABC: Autism Behavior Checklist, ATEC: Autism Treatment Evaluation Checklist, SOT: Sensory Organization Test, CABS: Clancy Autism Behavior Scale, TGMD3:

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Test of Gross Motor Development-3rd Edition, SRS: Social Responsiveness Scale, ASSS: Autism Social Skills Scale, SISS: Social Skills Improvement System, BOT-2: Social Skills Improvement System, IDC-10: International Classification of Diseases, 10th Revision.

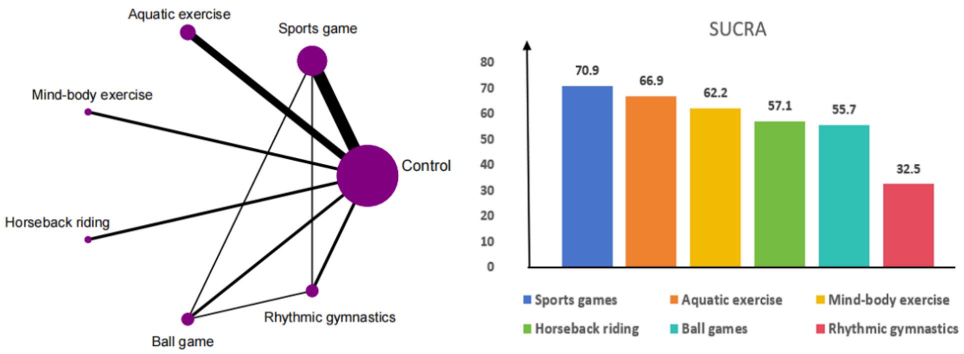
3.3 Result of Quality assessment

Based on the evaluation using the PEDro scale, among the 63 included studies, 29 were classified as high-quality literature with scores ranging from 8 to 11, while 34 were classified as moderate-quality literature with scores ranging from 4 to 7 (Table1).

3.4 Effects of different exercise therapies in ASD

3.4.1 Severity of autism symptoms

A total of 19 studies were included to assess the severity of ASD. The analysis covered six different exercise interventions: sports games, aquatic exercise, mind-body exercise, horseback riding therapy, ball games, and rhythmic gymnastics. The inconsistency test showed no significant inconsistencies in the results. All six interventions demonstrated efficacy in alleviating ASD severity, with the following effect sizes (SMDs): sports games [-0.79 (-1.15, -0.43), $p < 0.05$], aquatic exercise [-0.76 (-1.26, -0.27), $p < 0.05$], mind-body exercise [-0.73 (-1.52, 0.07), $p > 0.05$], horseback riding [-0.66 (-1.45, 0.13), $p > 0.05$], ball games [-0.64 (-1.36, 0.09), $p > 0.05$], and rhythmic gymnastics [-0.36 (-1.05, 0.33), $p > 0.05$]. The SUCRA ranking showed the following order of effectiveness: sports games (70.9) > aquatic exercise (66.9) > mind-body exercise (62.2) > horseback riding therapy (57.1) > ball games, (55.7) > rhythmic gymnastics (32.5) (Figure 2).



Sports games						
-0.02 (-0.64, 0.59)	Aquatic exercise					
-0.06 (-0.94, 0.82)	-0.04 (-0.97, 0.90)	Min-body exercise				
-0.13 (-1.00, 0.74)	-0.11 (-1.04, 0.82)	-0.07 (-1.19, 1.05)	Horseback riding			
-0.15 (-0.91, 0.60)	-0.13 (-1.01, 0.75)	-0.09 (-1.17, 1.00)	-0.02 (-1.09, 1.05)	Ball games		
-0.43 (-1.18, 0.32)	-0.40 (-1.25, 0.45)	-0.36 (-1.42, 0.69)	-0.30 (-1.34, 0.75)	-0.28 (-1.19, 0.64)	Rhythmic gymnastics	
-0.79 (-1.15, -0.43)	-0.76 (-1.26, -0.27)	-0.73 (-1.52, 0.07)	-0.66 (-1.45, 0.13)	-0.64 (-1.36, 0.09)	-0.36 (-1.05, 0.33)	Control

Figure 2 Network diagram and SUCRA ranking of the severity of autism treated with exercise therapy.

3.4.2 Social communication deficits

A total of 26 studies were included to evaluate social communication deficits in individuals with ASD. The analysis covered eight different exercise interventions: Taekwondo, hippotherapy, adaptive physical activity, sports games, aquatic exercise, mind-body exercise, ball games, and rhythmic gymnastics. All eight interventions demonstrated efficacy in mitigating the severity of ASD, with the following effect sizes (SMDs): Taekwondo [-0.99 (-2.16, 0.18), $p > 0.05$], adaptive physical activity [-0.70 (-1.69, 0.29), $p < 0.05$], sports games [-1.40 (-2.30, -0.50), $p < 0.05$], aquatic exercise [-0.40 (-1.37, 0.57), $p > 0.05$], mind-body exercise [-0.62 (-1.54, 0.30), $p > 0.05$], horseback riding [-1.45 (-2.47, -0.42), $p < 0.05$], ball games [-0.74 (-1.40, -0.07), $p < 0.05$], and rhythmic gymnastics [0.20 (-1.01, 1.42), $p > 0.05$]. The SUCRA ranking indicated the following order of effectiveness: horseback riding therapy (84.8) > sports games (83.2) > karate (65.1) > ball games (53.9) > adaptive physical activity (52.5) > mind-body exercise (47.1) > aquatic exercise (36.2) > rhythmic gymnastics (13.5) (Figure 3).

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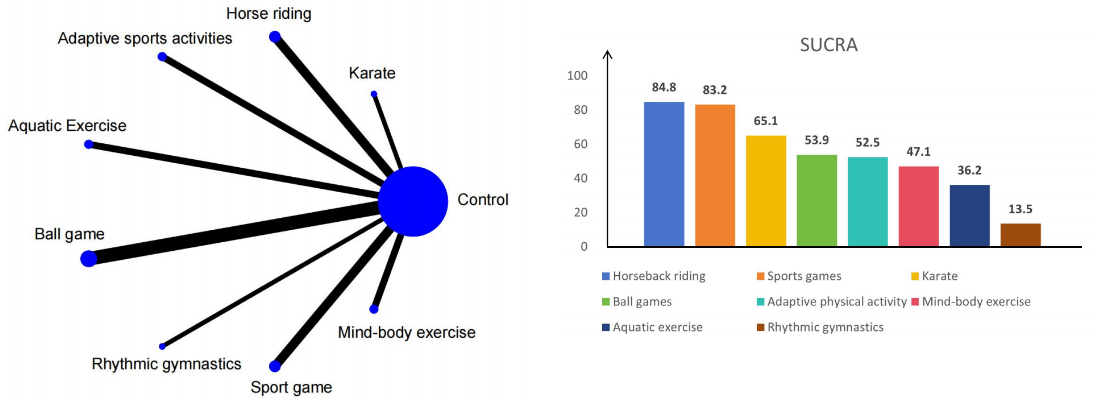

Control								
0.99 (−0.18, 2.16)	Karate							
1.45 (0.42, 2.47)	0.46 (−1.10, 2.01)	Horseback riding						
0.70 (−0.29, 1.69)	−0.29 (−1.82, 1.24)	−0.75 (−2.18, 0.68)	Adaptive physical activity					
0.40 (−0.57, 1.37)	−0.59 (−2.11, 0.93)	−1.05 (−2.46, 0.36)	−0.30 (−1.69, 1.09)	Aquatic exercise				
0.74 (0.07, 1.40)	−0.25 (−1.60, 1.09)	−0.71 (−1.93, 0.52)	0.04 (−1.16, 1.23)	0.34 (−0.84, 1.52)	Ball games			
−0.20 (−1.42, 1.01)	−1.19 (−2.88, 0.50)	−1.65 (−3.25, −0.05)	−0.90 (−2.47, 0.67)	−0.60 (−2.15, 0.96)	−0.94 (−2.32, 0.45)	Rhythmic gymnastics		
1.40 (0.50, 2.30)	0.41 (−1.07, 1.88)	−0.05 (−1.41, 1.31)	0.70 (−0.64, 2.04)	1.00 (−0.33, 2.32)	0.66 (−0.46, 1.78)	1.60 (0.09, 3.11)	Sports games	
0.62 (−0.30, 1.54)	−0.37 (−1.86, 1.12)	−0.82 (−2.20, 0.55)	−0.08 (−1.43, 1.28)	0.22 (−1.12, 1.56)	−0.12 (−1.25, 1.02)	0.82 (−0.70, 2.35)	−0.78 (−2.06, 0.51)	Mind-body exercise

Figure 3 Network diagram and SUCRA ranking of social communication deficits treated with exercise therapy.

3.4.3 Other behaviours

A total of 8 studies were included to assess stereotypical behaviors in ASD. Due to the limited number of studies, a traditional meta-analysis was conducted instead of NMA. The heterogeneity test yielded an I^2 value of 80.8%, necessitating the use of a random-effects model. The meta-analysis results indicated that exercise interventions effectively improved stereotypical behaviors in ASD [-0.66, 95% CI (-1.30, -0.02), $p < 0.05$] (table 2). Egger's test was performed to assess publication bias, resulting in $p = 0.133$, suggesting no significant publication bias in the analyzed studies. In addition, we explored the effects of exercise on various aspects of ASD, including social adaptability, motor skills, static balance, sensory abnormalities, emotional problems, quality of life, and executive function (Table2). Regarding social adaptability, 8 studies were included, with a heterogeneity test showing $I^2 = 86.3\%$, thus a random-effects model was used. Meta-analysis results indicated that exercise significantly improves social adaptability in individuals with ASD [0.89 (0.32, 1.55), $p < 0.05$]. For motor skills, 14 studies were included, with a heterogeneity test showing $I^2 = 85.0\%$, and a random-effects model was applied. The meta-analysis revealed that exercise effectively enhances motor skills in individuals with ASD [0.80 (0.22, 1.37), $p < 0.05$]. Regarding sensory abnormalities, seven studies were included, with heterogeneity testing revealing $I^2 = 94.2\%$, necessitating the use of a random-effects model. The meta-analysis demonstrated that exercise significantly reduces sensory abnormalities in ASD [-1.28 (-2.24, -0.31), $p < 0.05$]. For static balance, 10 studies were included, with a heterogeneity test showing $I^2 = 87\%$, thus a random-effects model was used. The results indicated that exercise significantly improves static balance in individuals with ASD [2.03 (1.12, 2.93), $p < 0.05$]. For dynamic balance, five studies were included, with a heterogeneity test showing $I^2 = 91.2\%$, and a random-effects model was employed. The meta-analysis suggested that exercise did not significantly enhance dynamic balance in individuals with ASD [0.79 (-0.69, 2.27), $p > 0.05$]. Regarding emotional problems, 10 studies were included, with heterogeneity testing indicating $I^2 = 93.5\%$, requiring a random-effects model. The results showed that exercise did not significantly alleviate emotional problems in ASD [-0.92 (-2.27, 0.43), $p > 0.05$]. Concerning life quality 5 studies were included to assess, with a heterogeneity test showing $I^2 = 89.8\%$, thus a random-effects model was used. The meta-analysis results suggested that exercise did not significantly improve the quality of life in individuals with ASD [0.27 (-0.49, 1.03), $p > 0.05$]. Lastly, for executive function, 4 studies were included, with a heterogeneity test indicating $I^2 = 0\%$, allowing for the use of a fixed-effects model. The meta-analysis revealed that exercise significantly improves executive function in individuals with ASD [-0.38 (-0.74, -0.01), $p < 0.05$].

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Table 2 Result of meta-analysis

Outcomes	Studies	I^2 (%)	Model	Result of meat analysis	
				SMD (95%CI)	*P*
Stereotypy	8	80.8%	Random	-0.66 (-1.30, -0.02)	<0.05
Social adaptability	8	85.0%	Random	0.80(0.22, 1.37)	<0.05
Motor skills	14	88.6%	Random	1.11(0.42, 1.81)	<0.05
Sensory abnormalities	7	94.2%	Random	-1.28(-2.24, -0.31)	<0.05
Dynamic balance	10	87%	Random	2.03(1.12, 2.93)	<0.05
Static balance	5	91.2%	Random	0.79(-0.69, 2.27)	>0.05
Emotional issues	5	93.5%	Random	-0.92(-2.27, 0.43)	>0.05
Life quality	5	89.8%	Random	0.27(-0.49, 1.03)	>0.05
Executive function	4	0%	Fixed	-0.38(-0.74, -0.01)	<0.05

3.5 Dose-Response Analysis of Exercise Interventions for ASD

Meta-analysis conducted after classifying exercise intervention periods revealed that interventions lasting longer than 12 weeks produced better outcomes in reducing autism severity and alleviating social communication deficits in ASD patients [Severity of autism symptoms: -1.12 (-1.52, -0.73)] (Table3). Further classification of studies with interventions exceeding 12 weeks showed that a frequency of at least three sessions per week yielded more significant improvements [Severity of autism symptoms: -1.44 (-2.09, -0.79)] (Table3). Additional classification of studies involving more than three sessions per week indicated that exercise programs with session durations of ≥60 minutes were more effective in ASD interventions [Severity of autism symptoms: -1.04 (-1.54, -0.54)] (Table3). Therefore, when designing exercise intervention programs for ASD, it is recommended to implement a regimen lasting more than 12 weeks, with sessions conducted at least three times per week, and each session lasting over 60 minutes.

Table 3 Comparison of intervention duration.

Outcomes	Studies	I^2 (%)	Model	Result of meat analysis	
Severity of autism symptoms				SMD (95%CI)	*P*
≤12 weeks	10	35.9	Fixed	-0.54 (-0.80, -0.27)	*P*<0.05
>12 weeks	11	68.5	Random	-1.12 (-1.52, -0.73)	*P*<0.05
<3 times	4	0	Fixed	-0.81 (-1.15, -0.48)	*P*<0.05
≥3 times	7	80.4	Random	-1.44 (-2.09, -0.79)	*P*<0.05
<60 min	2	0	Fixed	-1.04 (-1.54, -0.54)	*P*<0.05
≥60 min	4	90	Random	-2.12 (-3.68, -0.56)	*P*<0.05

4. Discussion

This study aimed to comprehensively evaluate the effects of exercise on ASD. The results indicated that, in terms of reducing the severity of autism symptoms, sports games were the most effective. For improving social communication deficits, horseback therapy was the most effective. Additionally, exercise was found to significantly improve social adaptability, motor skills, sensory abnormalities, static balance, and executive function in individuals with ASD. However, exercise had limited effects on dynamic balance, quality of life, and emotional problems. Dose-response analysis revealed that interventions lasting more than 12 weeks, with a frequency of at least three times per week and a duration of 60 minutes or more per session, yielded the best outcomes.

In recent years, exercise has gained widespread recognition as an effective behavioral intervention for improving ASD symptoms. Numerous studies have demonstrated the effectiveness of exercise interventions in enhancing social communication deficits, reducing repetitive and stereotyped behaviors, improving executive function and motor skills, and even addressing sleep disturbances in individuals with ASD[9, 80].The exploration of potential mechanisms underlying these benefits has focused on several areas: exercise-induced changes in brain structural integrity, synaptic plasticity, neurotransmitter release, gut microbiota modulation via the gut-brain axis, and reduction of neuroinflammation in the brain[10, 81, 82].

However, several challenges remain in developing exercise prescriptions for ASD interventions. These include the need for more scientific selection of exercise types, clarification of appropriate intervention duration and dosage, and identification of the optimal age for intervention. The results of this study identified sports games and horseback interventions as particularly effective exercise interventions for ASD. Sports games, widely used in ASD interventions, offer a flexible approach that

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can be customized to include elements of aerobic exercise, resistance training, basic motor skills, speed, strength, and agility development, thereby providing better outcomes for individuals with ASD[83]. This method's simplicity and high degree of personalization are its strengths, but the same customization makes it difficult to standardize the exercise content, leading to challenges in establishing a standardized reference protocol for ASD sports games. Horseback-riding therapy, involving animal-assisted interventions (AAT), is another effective method. Many healthcare professionals and therapists use AAT to enhance participation in physical activities, relieve psychological stress and anxiety, and create environments that foster social interaction and communication through interactions with animals[84]. A 10-week horseback riding therapy program has been shown to improve self-regulation behaviors, adaptive skills, and motor skills in children and adolescents with ASD[85]. Additionally, a meta-analysis confirmed the effectiveness of horseback-riding therapy in improving social communication deficits in individuals with ASD[86]. This indicates the widespread application of such research in the field of autism.

Frequency and duration of physical exercise are key factors in the effectiveness of interventions. Engaging in physical activity more than three times a week has been identified as an effective dose for reducing stereotyped behaviors in children with ASD[87]. This study explored the optimal duration of ASD interventions and found that interventions lasting more than 12 weeks, with a frequency of three sessions per week, each lasting at least 60 minutes, yielded the best results. This finding is consistent with previous research by Wang[9], which also suggested interventions lasting more than 12 weeks, with a frequency of three sessions per week and each session lasting 90 minutes, were more effective. However, some inaccuracies appear to exist in Wang's study, as it did not account for the impact of the duration on the weekly frequency of interventions, nor did it consider the impact of the total intervention period and weekly frequency on the duration of each session. In contrast, this study classified interventions based on a 12-week threshold, and further analysis revealed that interventions longer than 12 weeks, conducted three times per week, and lasting 60 minutes per session, were more effective, providing a more robust basis for these recommendations.

5. Conclusion

Sports games, horseback riding therapy are the optimal choices for ASD exercise therapies. The best dosage for ASD exercise intervention involves interventions lasting over 12 weeks, with sessions at least three times per week, each lasting 60 minutes or longer.

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