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The canonical correlation between executive function and social skills in children with autism spectrum disorder and potential pathways to physical fitness

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Research on the relationship between core and comorbid features in children with Autism Spectrum Disorder (ASD), particularly executive function, remains limited. Additionally, the role of physical fitness in supporting ASD children's growth and development appears critical. This study investigates the relationship between executive function, social skills, and physical health in children with ASD. A total of 428 male participants were enrolled, including 117 diagnosed with ASD (mean age: 10.25 ± 1.481 years) and 311 with typical development (mean age: 9.56 ± 1.261 years). The results showed that children with ASD had significantly lower executive function and social interaction abilities than those with typical development ($P < 0.05$). A strong correlation was found between executive function and social skills (first canonical correlation coefficient: 0.641, $P < 0.001$), with 20.4% of the variation in social abilities explained by executive function. Specifically, emotional control, working memory, social perception, social cognition, and autistic behaviors influenced ASD children's development. While balance did not correlate significantly with physical fitness ($P > 0.05$), muscle strength showed a stronger effect (r = -0.485 to -0.535, $P < 0.05$). Improving physical fitness may help alleviate deficits in executive function and social skills. These findings provide early insights into the relationship between executive function and social skills in ASD, emphasizing the potential role of physical activity.

Keywords Executive function, Social skill, Physical fitness, Autism, Relationship

Autism Spectrum Disorder (ASD) is a neurodevelopmental disorder characterized by persistent deficits in social communication and interaction, alongside restricted and repetitive behaviors. Children with ASD typically experience difficulties in forming and maintaining peer relationships, which are developmentally appropriate, manifesting as challenges in social interaction, nonverbal communication, and the development, maintenance, and comprehension of complex interpersonal relationships[1]. Research indicates a rising global incidence of ASD, with an overall prevalence of approximately 1.5% in developed countries. In 2021, the CDC reported a prevalence of 2.47% among children aged 0–8 years[2]. In China, clinical diagnostic standards show a prevalence rate of 0.39%[3]. These figures highlight the significance of ASD as a public health concern, urging the need for more research into its causes and interventions[4].

A growing body of research suggests that executive function (EF) plays a critical role in various cognitive and behavioral challenges observed in children with ASD[5]. EF is conceptualized as a set of cognitive processes essential for self-regulation, problem-solving, and adaptive behavior, particularly in social contexts. According to Dawson and Guare's EF model[6], EF is composed of three core components: inhibitory control, cognitive flexibility, and working memory. These components work together to regulate behavior, maintain attention, and facilitate adaptive responses to the environment. Additionally, Zelazo's EF model[7] highlights the importance of emotional regulation and planning abilities, which are particularly relevant for social interactions, as they help

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individuals manage emotions and plan socially appropriate behaviors. These components collectively influence an individual's social functioning, including the ability to engage effectively in peer interactions.

Research has shown that deficits in EF, particularly in areas like inhibitory control and cognitive flexibility[8,9], can significantly hinder a child's ability to navigate social interactions effectively[10]. Children with ASD often experience challenges in managing emotional responses[11,12], shifting attention between tasks, and maintaining appropriate behavior in social situations, all of which are key functions of EF[13]. These difficulties are directly linked to social communication disorders (SCD), which include problems such as initiating or maintaining conversations, interpreting social cues, and responding to social norms[14]. For example, children with impaired EF often struggle to regulate their emotions during social interactions[15,16], leading to anxiety, irritability, or withdrawal, which in turn exacerbates social isolation[17]. Moreover, the inability to shift attention or suppress impulsive responses can result in inappropriate social behaviors, further hindering peer relationships. These EF deficits, particularly when combined with difficulties in social communication, contribute to the persistence of social challenges in children with ASD[18,19].

Motor dysfunction, often considered a comorbidity in ASD[20], is characterized by difficulties in flexibility, agility, cardiorespiratory endurance, and muscle strength. Although some studies classify these motor deficits as a comorbidity, research has also suggested that they could be considered part of the broader clinical presentation of ASD[21,22]. Children with motor dysfunction may exhibit delayed or impaired coordination, which can hinder their participation in physical activities and impact social interactions[23] (Bhat, 2015). Furthermore, research on hypermobility has shown that children with ASD are at an increased risk for joint hypermobility, which can lead to difficulties in motor control and coordination[24]. These motor impairments not only affect physical development but also hinder social engagement, as motor coordination can influence a child's ability to participate in joint activities with peers and caregivers[25]. Cross-sectional studies[26] have demonstrated significant correlations between muscle strength, body mass index, EF, and information processing in children with ASD, suggesting that physical fitness may play an integral role in both EF and social skills development[27].

Building upon previous studies, this paper adopts a cross-sectional design to clarify differences in EF and social skills between children with ASD and typically developing children. Additionally, this study explores the relationship between physical fitness, EF, and social interaction difficulties in children with ASD, providing valuable insights for clinical practice and future research directions. Specifically, we hypothesize that improvements in physical fitness could positively impact EF and, in turn, enhance social communication abilities in children with ASD, thus offering potential pathways for intervention.

Research objects and methods

Recruitment of participants

The method of convenience sampling was adopted in this paper. Specifically, 117 children with autism were recruited from special education schools in Guangzhou, Shenzhen, Zhuhai, Foshan, Zhongshan and other Pearl River Delta cities, and 311 ordinary children were recruited from ordinary schools in the above five cities. Vigorous exercise within 24 h prior to the test and drinking caffeinated or alcoholic beverages were not allowed. Additionally, participants needed to avoid an empty stomach or a full stomach during the test. Before the experiment, all participants were aware of the measurement process and possible risks, and all of them signed informed consent with their parents. This study has been approved by the Ethics Committee of Shanghai University of Sport (102772020RT061) and met the ethical standards set out in the "Declaration of Helsinki" (revised in 2008). All subjects signed an informed consent form indicating their consent to participate in the study.

Criteria for the inclusion and exclusion of autistic children

Criteria for inclusion:

(1) All participants in this study received a confirmed diagnosis of autism from certified hospital clinicians, meeting the diagnostic criteria specified in the fifth edition of the *Diagnostic and Statistical Manual of Mental Disorders* (DSM-5), as published by the American Psychiatric Association;
(2) Children from grades 1 to 6;
(3) Before the test, the physical education teachers of special education schools were fully communicated, to ensure that the children included in test could complete the test and relatively simple physical activities with the support and help of the teachers.

Criteria for exclusion:

(1) Children diagnosed with autism who are unable to perform basic motor skills and health-related physical fitness assessments, even with the assistance and guidance of teachers;
(2) Children with autism who present with comorbid conditions, such as epilepsy, hearing impairments, or visual impairments, rendering them unsuitable for participation in physical exercise;
(3) Children with autism who display aggressive or other disruptive behaviors, thereby impeding the smooth execution of the study.

Exclusion case description: A total of three children diagnosed with autism were excluded from the study. One male participant, a 2nd-grade student (born in October 2016), was unable to complete the test, even with the assistance and guidance of the teacher. The remaining two participants were female, both 4th-grade students, born in May 2014 and March 2014, respectively.

Criteria for the inclusion and exclusion of typically developing children
Criteria for the inclusion and exclusion of typically developing children for test objects: Children who were able to cooperate with the test were included, and children who did not cooperate with the test were excluded. Since almost all the children with autism were boys in special education schools, male children were selected for the inclusion of ordinary children.

Exclusion case description: Four typically developing male participants were excluded from the study: two 1st-grade students (born in January 2018 and August 2017), one 2nd-grade student (born in January 2017), and one 6th-grade student (born in November 2012). These exclusions occurred due to the lack of parental signatures on the informed consent forms.

Measurement index and test methods
Test methods

(1) Physical function tests: The measurement index and test methods of the study were based on "National Student Physical Health Standard", and the data were collected, including body mass index (BMI), flexibility (sit-and-reach), vital capacity, muscle quality (grip strength, standing long jump) and balance quality (standing on one foot with eyes open). Details are shown in Table 1.

(2) Executive function: Behavior rating inventory of executive function (BRIEF) was used to evaluate the executive function of children with ASD in this study. The BRIEF assessed the executive function of children aged 6–18 at school (teacher scale) and at home (parent scale). The teacher scale of the BRIEF contained 86 items, and 8 factors were aggregated into two dimensions: the behavior management index (including three subscales: inhibition, conversion, and emotional control) and the metacognitive index (including five subscales: task initiation, working memory, planning, organizing, and monitoring). Each item was scored on a scale from 1 to 3. The higher the score, the more severely impaired the executive function. Qian Ying made a localized revision of the teacher scale of the BRIEF for school-age children and test the reliability and validity of the scale. The internal consistency of each factor and the total scale was high. Cronbach 'α coefficient was 0.73 ~ 0.98, and the retest reliability was 0.65 ~ 0.86, which indicated that the scale had the good reliability and validity, meaning that the scale could be used to assess the level of daily executive function of school-age children in the school environment, and it could distinguish between the executive function deficiency and the normal population, which was suitable for the Chinese cultural background[28]. The BRIEF is also commonly used to assess executive function in typically developing children, and it typically maintains high internal consistency. Teng, F. L, et al. (2017) reported that the Cronbach's α value for BRIEF in typically developing children was 0.89[29].

(3) Social skill: "Social Responsive Scale-Second Edition" (SRS-2) was an assessment tool commonly used to measure the social skills of children with ASD. SRS-2 quantified social skills to identify and assess social impairments in children with ASD, mainly assessing their ability to communicate, interpersonal behaviors, restricted and repetitive behaviors. The higher the score of the scale, the more severe the social interaction disorder. The lower the score of the scale, the better the development of social skill. The internal consistency of each factor and the total scale was high. Cronbach 'α coefficient of total scale was 0.946, and each dimension ranged from 0.563 to 0.944[30]. The SRS-2 demonstrates high internal consistency in typically

Test items	Test tools	Test methods
Body mass index (BMI)	Body Mass Index (BMI) Calculator (OMRON HBF-306).	The participants were asked to take off their shoes and hold themselves upright.
Flexibility	Adjustable Flexibility Testers (DELI FT303).	The participants were asked to take off their shoes and sit on a flat mat, with their back against the wall, arms straight, palms down and hands on the test instrument board, legs straight. In formal test, they needed to bend the upper body forward and push the tester gently forward until they couldn't push it any further. The results were recorded in cm.
Vital capacity	Lungtest Handy (Norenka TRX, with the scale interval of 1 ml).	During the test, the participants first did the maximum inhalation, and then tried to do the maximum exhalation into the mouthpiece. The exhalation process needed to be continuous, and they couldn't do the supplementary inhalation action during the exhalation process until the end of the blow. Each participant needed to be measured for three times, and the highest value of the three measurements was reported as their vital capacity. The results were recorded in ml.
Muscular fitness	Smart electronic hand-grip dynamometer (Condo EH106, with the scale interval of 0.1 kg) for grip strength test; Standing long jump mat (Rubber size: 2.5 m in length, 0.9 m in width, and 3.5 mm in thickness; with the scale interval of 1 cm) for standing long jump test.	Smart electronic hand-grip dynamometer (Condo EH106, with the scale interval of 0.1 kg) was used to measure grip strength. During the test, the participant used the dominant hand to perform the test. Each participant needed to be measured for three times, and the highest value of the three measurements was reported as their result of grip strength. The results were recorded in kg. Standing long jump mat (Rubber size: 2.5 m in length, 0.9 m in width, and 3.5 mm in thickness; with the scale interval of 1 cm) was used to do the standing long jump test. Each participant needed to be measured for three times, and the best result of the three measurements was reported as their final result of standing long jump. The results were recorded in cm.
Balance quality	The index of standing on one foot with eyes open reflected the balance ability of the participants.	The participants should stand on the dominant leg, with hands on the waist and the foot of the other leg placed at the knee of the supporting leg. After the "start" signal, the participants' body needed to remain as still as possible until they cannot persist. We calculated the time between the start and the imbalance of the participants. Each participant needed to be measured for three times, and the best result of the three measurements was reported as their final result of balance quality. The results were recorded in s.

Table 1. Tools and methods for physical function test.

developing children. Korkmaz, H. B., et al. (2018) found that the Cronbach's α value for SRS-2 in typically developing children was 0.91[31], indicating that the scale also exhibits excellent internal consistency within this group.

Test process

The sampling period for this test was from September to December in 2020. Children with ASD were sampled from September to November in 2020, and children with typical development were sampled in December. All tests were conducted with parental consent and were conducted during non-teaching time with the help of the class teacher. The tests (including basic information collection and physical fitness test, executive function and social interaction ability assessment) were conducted between 2:30 p.m. and 4:30 p.m. The test process was shown in Fig. 1.

Statistical methods

Data analysis in this study was performed using SPSS 26.0 (IBM Corp., Armonk, NY, USA) and GraphPad Prism 9.0.

Data distribution was initially examined using frequency histograms. For measurement data that conformed to a normal distribution or approximately normal distribution, descriptive statistics were presented as means ± standard deviation (X ± SD). The independent sample t-test was used for comparisons between groups. For measurement data that exhibited significantly skewed distributions, median values (interquartile range) [M (P25, P75)] were reported, and the Mann-Whitney U non-parametric test was employed for group comparisons. Pearson correlation coefficient analysis was used to explore the relationship between executive function (EF) and social skills in children with autism spectrum disorder (ASD).

To further investigate the relationships among various dimensions of executive function and social skills in children with ASD, canonical correlation analysis (CCA) was performed. This analysis involved the construction of standardized canonical models, canonical structure analysis, and canonical redundancy analysis. All variables were standardized prior to the analysis to ensure comparability. Canonical correlation analysis was conducted using SPSS version 26.0 (IBM Corp., Armonk, NY, USA). The significance level for all tests was set at $p < 0.05$.

Canonical correlation analysis

Canonical correlation analysis is a multivariate statistical method that investigates the linear relationship between two sets of variables. In this study, the dimensions of executive function (EF) and social skills were treated as two distinct sets of variables. Canonical correlation analysis identifies statistically significant pairs of variables, and the correlation coefficients between these pairs are used to quantify the relationship between the two sets.

The canonical correlation coefficient (r) quantifies the strength of the relationship between the two variable sets. The value of r ranges from 0 to 1, with values closer to 1 indicating a stronger linear relationship. For this study, $|r| > 0.7$ was considered a strong correlation.Each pair of canonical variables is associated with an eigenvalue, which represents the variance explained by that pair. Larger eigenvalues indicate stronger relationships between the two sets. The cumulative proportion of the eigenvalues was calculated, and pairs of canonical variables with a cumulative contribution ratio exceeding 50% were prioritized for further analysis.Canonical structure analysis examines the weights of each variable in the canonical variable. These weights represent the strength of each variable's contribution to the canonical variable. Higher weight values suggest greater significance in the relationship between the two variable sets.Canonical redundancy analysis measures the degree to which each canonical variable explains variance in the other set of variables. This analysis quantifies the shared information

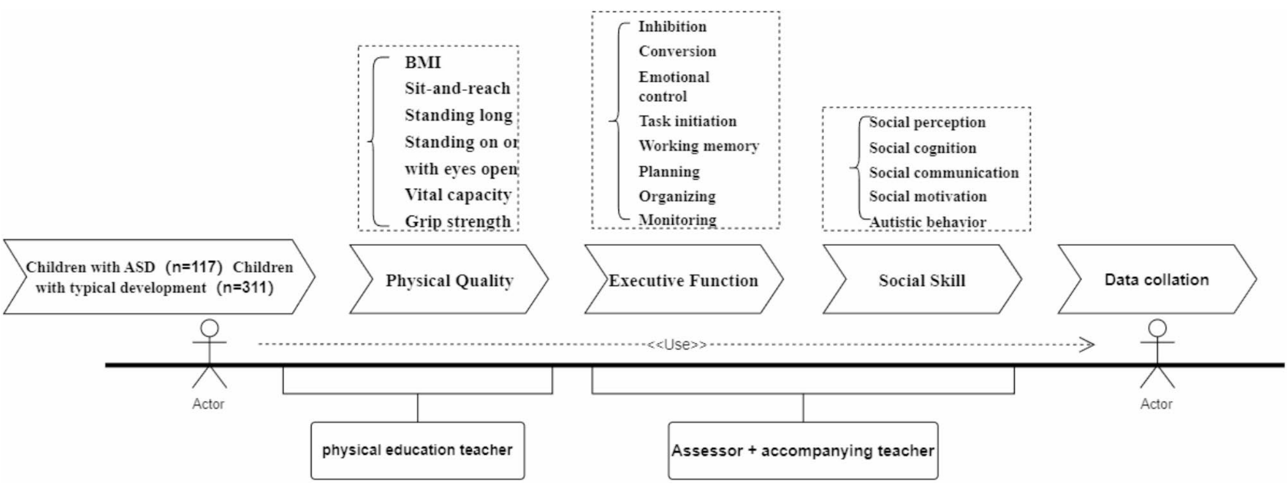

Fig. 1. Test process.

between the two sets, providing further insights into the relationship between executive function and social skills.

Additional statistical analyses

One-way analysis of variance (ANOVA) and LSD post-hoc multiple comparisons were conducted to compare the executive function and social skills of children with ASD at different levels of physical fitness. A two-tailed test was used for statistical inference of all parameters, and the test level was set at $\alpha = 0.05$. p-values of < 0.05, < 0.01, and < 0.001 were considered statistically significant.

Results

Common method Bias test

An exploratory factor analysis of the variables was conducted using the Harman single-factor test. The analysis revealed that six factors exhibited eigenvalues exceeding 1, with the first factor accounting for 32.50% of the variance, which is below the 40% threshold, suggesting that there is no substantial common method bias in this study.

Specificity of executive function and social skill in children with ASD

A total of 117 male participants diagnosed with autism were enrolled in this study, with a mean age of 10.25 ± 1.481 years. Additionally, 311 typically developing participants were included, with a mean age of 9.56 ± 1.261 years, spanning grades 1 through 6. The results indicated no statistically significant difference in age between participants with autism and their typically developing counterparts ($P > 0.05$). However, significant differences were observed between the two groups concerning executive function, social interaction abilities, and health-related physical fitness indicators ($P < 0.05$). These findings indicate that participants with autism demonstrated lower scores than typically developing participants in both executive function and social interaction abilities. Details are shown in Table 2.

The relationship between executive function and social skill in children with ASD

Pearson correlation analysis was conducted to explore the executive function and social skill of children with ASD. As shown in Table 3, there was a significant positive correlation between executive function and social skill in children with ASD ($P < 0.01$), which provided a basis for the subsequent canonical correlation analysis.

The canonical correlation analysis was conducted to explore the relationship between executive function and two dimensions of the social skill. The canonical variable was a comprehensive index extracted based on the principle of maximizing the correlation between the two groups of indexed. As shown in Table 4, five pairs of canonical variables were extracted from each group. The results revealed that the first pair of canonical variables showed significance ($P < 0.001$), the canonical correlation coefficient was 0.641, and the proportion of cumulative eigenvalue was 69.7%, suggesting that the first pair of canonical variables explained 69.7% of the correlation between the dimensions of executive function and social skill. Since the coefficients of the remaining pairs were low and didn't show significance, only the first pair of canonical variables was analyzed. In order to facilitate the analysis, the first pair of canonical variables were named Z and S, where Z was mainly used to extract information of various dimensions of executive function, and S was mainly used to extract information of various levels of social skill.

As shown in Fig. 2, among children with ASD, Z had a higher load factor for emotional control and working memory, while S had a higher load rate for social perception, social cognition and autistic behavior, indicating that there might be synchronous indexes of executive function disorder and social interaction disorder in children with ASD.

Variables	Children with ASD($n = 117$)	Children with typical development($n = 311$)	Difference test
Total score of executive function	214.214 ± 7.012	95.656 ± 4.942	t = 1.511, $P < 0.001$
Inhibition	48(46, 49)	21(20, 22)	Z=−16.190, $P < 0.001$
Conversion	28(26.5, 28)	12(12, 13)	Z=−16.424, $P < 0.001$
Emotional control	33.179 ± 1.901	15.965 ± 1.747	t = 1.407, $P < 0.001$
Task initiation	22.855 ± 0.985	11.235 ± 1.407	t = 3.577, $P < 0.001$
Working memory	27.795 ± 1.399	13.521 ± 3.577	t = 0.897, $P < 0.001$
Planning	16.333 ± 1.009	7.051 ± 0.897	t = 2.046, $P < 0.001$
Organizing	31(30, 32)	11(9, 12)	Z=−16.087, $P < 0.001$
Monitoring	8.077 ± 0.659	3.479 ± 0.761	t = 4.942, $P < 0.001$
Total score of social skill	142.880 ± 10.903	36.270 ± 2.249	t = 0.898, $P < 0.001$
Social perception	16.906 ± 1.880	5.810 ± 0.898	t = 1.174, $P < 0.001$
Social cognition	27.598 ± 2.301	8.074 ± 1.174	t = 0.974, $P < 0.001$
Social communication	49.855 ± 5.125	10.711 ± 0.974	t = 0.784, $P < 0.001$
Social motivation	22(20, 25)	7(6, 7)	Z=−16.434, $P < 0.001$
Autistic behavior	26.017 ± 2.519	4.711 ± 0.573	t = 140.077, $P < 0.001$

Table 2. Specificity of executive function and social skill in children with ASD.

Index	Social perception	Social cognition	Social communication	Social motivation	Autistic behavior
Inhibition	0.372**	0.370**	0.271**	0.073	0.380**
Conversion	0.219*	0.211*	0.292**	0.066	0.264**
Emotional control	0.352**	0.407**	0.323**	0.078	0.417**
Task initiation	0.249**	0.282**	0.211*	−0.001	0.196*
Working memory	0.419**	0.403**	0.266**	0.114	0.410**
Planning	0.094	0.069	0.123	−0.074	0.201*
Organizing	0.081	−0.014	0.003	0.073	0.024
Monitoring	0.110	0.214*	0.246**	0.083	0.238*

Table 3. Correlation coefficient matrix between executive function and social skill. * and ** indicated $P<0.05$ and $P<0.01$ respectively.

			Significance test			
Canonical variable pair	Canonical correlation coefficient	Proportion of cumulative eigenvalue /%	Wilks'	Chi-SQ	F	*P*
1	0.641	0.697	0.479	456.120	2.097	< 0.001
2	0.349	0.829	0.813	380.005	0.801	0.756
3	0.179	0.862	0.926	300.299	0.458	0.973
4	0.167	0.891	0.957	214.000	0.477	0.904
5	0.126	0.907	0.984	108.000	0.434	0.784

Table 4. Canonical correlation coefficient and significance.

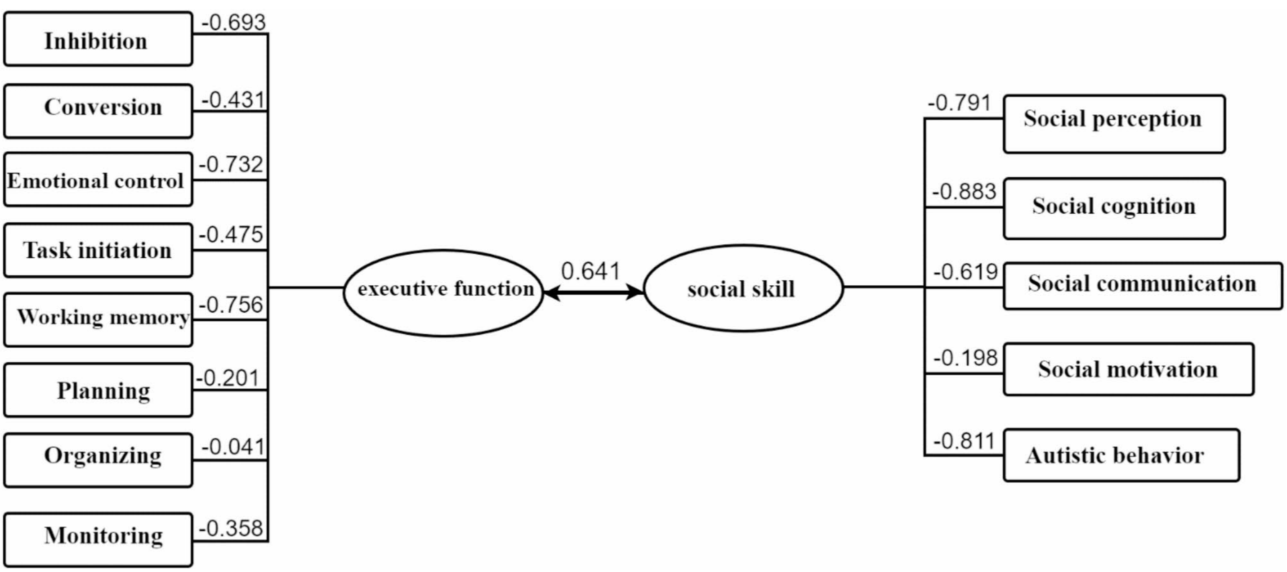

Fig. 2. Load coefficient of canonical correlation analysis.

The Canonical redundancy analysis took the variance ratio of the original variable explained by the canonical variable as the index to evaluate the ability of the canonical variable to explain the information contained in the original variable. The canonical variable Z explained 27.1% of the standardized variance of the original variable (executive function), and 11.1% of the standardized variance of the original variable (social skill), while the canonical variable S explained 49.7% of the standardized variance of the original variable (social skill), and 20.4% of the standardized variance of the original variable (executive function), meaning that 20.4% of the variation in social skill in children with ASD was related to executive function.

The relationship between physical fitness and executive function as well as social skill in children with ASD

The results of canonical correlation analysis showed that the executive function disorder and social interaction disorder of children in ASD were mainly determined by emotional control, working memory, social perception, social cognition and autistic behavior, and they were closely related to each other, and they had strong correlation with them. Therefore, this study also analyzed the relationship between these specific symptoms and physical fitness. Details are shown in Table 5.

As to the difference of body composition, there existed significant difference in the scores of emotional control, social perception and autistic behavior between the high level group and the low level group ($P < 0.05$), and there existed significant difference of some scores between middle and low level groups ($P < 0.05$). As for the difference of the sit-and-reach, there existed significant difference in the scores of emotional control, working memory, social perception, social cognition and autistic behavior between the high level group and the low level group ($P < 0.05$), and there existed significant difference between middle and low level groups ($P < 0.05$). Furthermore, as to the difference of standing long jump, there existed significant difference in the scores of emotional control, working memory, social perception, social cognition and autistic behavior between the high level group and the low level group ($P < 0.05$), and most of the middle and low level groups also had significant difference in scores ($P < 0.05$). In addition, as to standing on one foot with eyes open, there was no significant difference in scores of each dimension ($P > 0.05$). As to the vital capacity, the results showed that there existed significant difference in the scores of social cognition and autistic behavior between the high level group and the low level group, and some scores in the middle and low level group were significantly different ($P < 0.05$). Finally, as for the grip strength, there existed significant difference in the scores of working memory, social perception, social cognition and autistic behavior between the high level group and the low level group, and there existed significant difference between middle and low level groups in each dimension ($P < 0.05$). Details are shown in Fig. 3.

As shown in Table 6, body composition, standing long jump, vital capacity and grip strength of children with ASD were negatively correlated with each dimension, and most of them were significan($P > 0.05$)t. The score of sit-and-reach was positively correlated with all dimensions ($P < 0.001$), but there was no significant correlation between the score of standing on one foot with eyes open and each dimension ($P > 0.05$). Basically, grip strength had the strongest correlation, and social perception was most closely related with the score of sit-and-reach.

Discussion

This study demonstrates that children with Autism Spectrum Disorder (ASD) exhibit deficits across all dimensions of executive functioning compared to typically developing peers, and a significant relationship was identified between executive functioning and social impairments. It was observed that working memory and emotional regulation within executive functioning are closely linked to social perception, social cognition, and autism-related behaviors in social skills, diverging from findings in previous research[5]. Most health-related physical fitness indicators were found to be significantly correlated with executive functioning and social interaction abilities, but balance ability did not exhibit any association with these dimensions, whereas muscular strength emerged as a critical factor.

This study identified a strong correlation between executive functioning and social impairments, with synchronous indicators linking these domains. Deficits in day-to-day executive functioning are closely associated with heightened feelings of isolation and diminished peer interactions in children with ASD. The common manifestations of executive function deficits appear to reflect comorbid conditions rather than constituting a distinct disorder characterized by isolated impairments[32,33]. Social interaction and communication difficulties in

Physical fitness		Executive function		Social skill		
		Emotional control	Working memory	Social perception	Social cognition	Autistic behavior
BMI	Low	33.54 ± 1.872	27.95 ± 1.361	16.95 ± 1.907	27.88 ± 2.159	26.35 ± 2.677
	Medium	32.33 ± 1.606	27.46 ± 1.503	17.25 ± 1.824	27.21 ± 2.813	25.63 ± 1.837
	High	32.11 ± 1.965	27.22 ± 1.302	15.56 ± 1.236	26.00 ± 1.225	24.00 ± 1.323
Sit-and-reach	Low	32.56 ± 1.764	27.35 ± 1.143	16.12 ± 1.714	26.55 ± 1.858	26.94 ± 2.661
	Medium	33.75 ± 1.826	28.19 ± 1.546	17.47 ± 1.404	28.44 ± 1.934	25.52 ± 2.241
	High	34.53 ± 1.598	28.80 ± 1.320	19.00 ± 1.512	30.20 ± 2.042	25.05 ± 2.179
Standing long jump	Low	33.77 ± 1.938	28.00 ± 1.444	17.50 ± 2.032	28.31 ± 2.468	26.07 ± 2.530
	Medium	32.88 ± 1.794	27.83 ± 1.404	16.54 ± 1.845	27.10 ± 2.309	26.17 ± 2.588
	High	32.52 ± 1.750	27.24 ± 1.179	16.38 ± 1.161	27.10 ± 1.338	25.82 ± 2.516
Standing on one foot with eyes open	Low	33.22 ± 1.878	27.88 ± 1.485	17.05 ± 1.863	27.60 ± 2.592	26.73 ± 2.560
	Medium	33.39 ± 1.672	27.52 ± 0.994	16.43 ± 1.903	27.61 ± 2.231	25.68 ± 2.453
	High	32.97 ± 2.110	27.82 ± 1.487	16.97 ± 1.899	27.59 ± 1.811	25.44 ± 2.394
Vital capacity	Low	33.85 ± 1.333	27.66 ± 1.460	17.59 ± 2.061	28.20 ± 2.750	26.73 ± 2.560
	Medium	32.62 ± 2.100	27.73 ± 1.326	16.57 ± 1.466	27.35 ± 1.929	25.68 ± 2.453
	High	33.56 ± 1.788	28.38 ± 1.455	16.44 ± 2.366	27.00 ± 2.129	25.44 ± 2.394
Grip strength	Low	33.94 ± 1.629	28.27 ± 1.373	17.42 ± 2.026	28.52 ± 2.097	26.96 ± 2.588
	Medium	31.93 ± 1.694	27.10 ± 1.068	16.24 ± 1.280	26.15 ± 1.944	24.68 ± 1.507
	High	32.60 ± 1.673	26.80 ± 1.483	15.00 ± 0.707	26.40 ± 0.548	23.60 ± 1.673

Table 5. Comparison of executive function and social skill scores of children with ASD among different physical fitness levels.

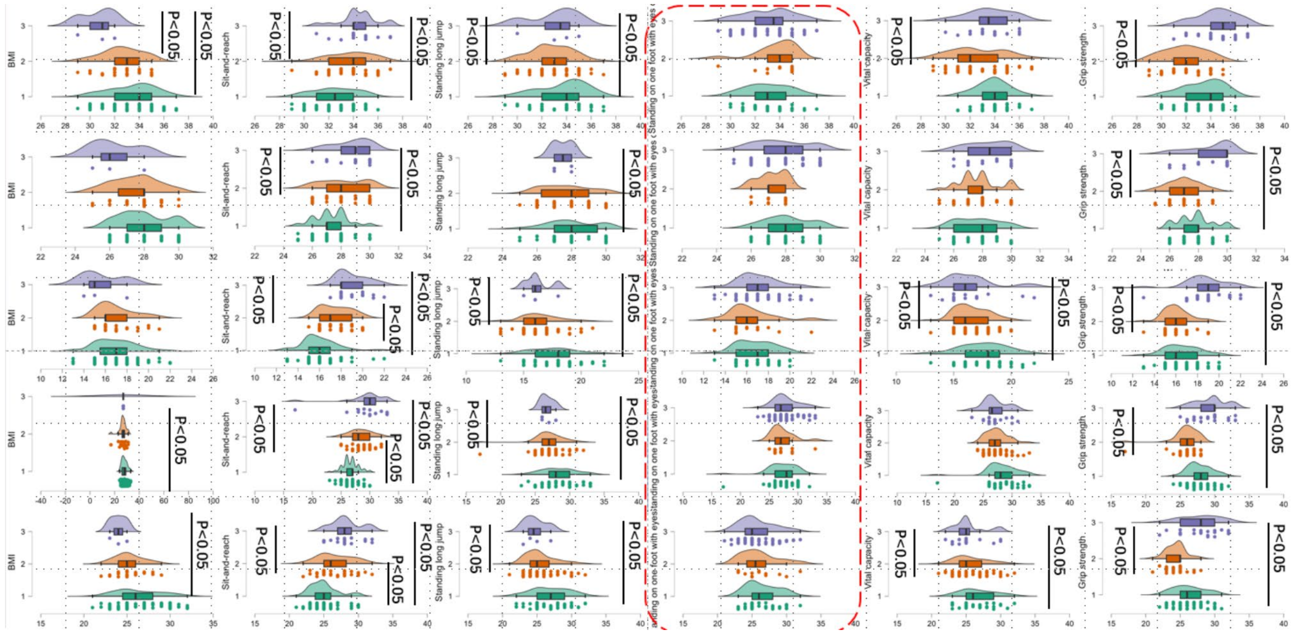

Fig. 3. Comparison of the disorder situation of children with ASD among different physical fitness levels Note: First column: Emotional control; The second column: Working memory; The third column: Social Perception; Fourth column: Social Cognition; The fifth column: Autistic behavior.

Index	Physical fitness					
	BMI	Sit-and-reach	Standing long jump	Standing on one foot with eyes open	Vital capacity	Grip strength
Emotional control	r=-0.381,P < 0.001	r = 0.327,P < 0.001	r=-0.276,P = 0.003	r = 0.000,P = 0.996	r=-0.196,P = 0.034	r=-0.485,P < 0.001
Working memory	r=-0.205,P = 0.026	r = 0.368,P < 0.001	r=-0.146,P = 0.116	r=-0.085,P = 0.362	r = 0.048,P = 0.609	r=-0.495,P < 0.001
Social perception	r=-0.185,P = 0.045	r = 0.515,P < 0.001	r=-0.191,P = 0.039	r=-0.101,P = 0.276	r=-0.235,P = 0.011	r=-0.505,P < 0.001
Social cognition	r=-0.248,P = 0.007	r = 0.388,P < 0.001	r=-0.226,P = 0.014	r=-0.040,P = 0.667	r=-0.218,P = 0.018	r=-0.520,P < 0.001
Autistic behavior	r=-0.287,P = 0.002	r = 0.424,P < 0.001	r=-0.297,P = 0.001	r = 0.098,P = 0.291	r=-0.223,P = 0.016	r=-0.535,P < 0.001

Table 6. The correlation between six indexes of physical fitness and each dimension.

individuals with ASD can be attributed to deficits in "hot" executive functions, which are integral to social and emotional processing[34]. Conversely, their stereotyped behaviors, restricted interests, and rigid mannerisms are explained by deficits in "cold" executive functions, which pertain to non-emotional tasks[35,36]. Social interaction and communication require the activation of multiple executive functions, such as goal setting (e.g., interaction goals, communication intentions), planning and organization (e.g., selecting and coordinating interaction and communication strategies), self-monitoring (e.g., tracking the interaction and communication process), and evaluating outcomes (e.g., assessing the results of interaction and communication)[9].

Additionally, canonical correlation analysis revealed stronger associations between working memory and emotional control with social perception, social cognition, and autism-related behaviors. Firstly, working memory, as a system for temporary storage and processing of information, is central to higher cognitive activities. Previous research has shown a relationship between visual working memory capacity and social interaction difficulties, where higher visual working memory capacity correlates with lower levels of social interaction difficulties[37,38]. For children with ASD, understanding others' intentions may involve more cognitive abilities[16,39], such as reasoning and inference, which are intricately linked to working memory. Furthermore, executive functions and language skills are interconnected, with vocabulary, grammar, and pragmatics in ASD children correlating with working memory, shifting, and inhibition within executive function domains[10,40]. Secondly, emotional regulation helps individuals manage immediate emotional responses in specific situations, allowing for appropriate reactions and reducing impulsivity[15,41]. Children with ASD exhibit poor emotional regulation and difficulty understanding others' emotions, which can lead to autistic behaviors[42]. Social interactions, such as adopting others' perspectives and maintaining reciprocal and proactive social exchanges, are related to emotional regulation. Therefore, future research could explore the relationship between executive functions and social interaction deficits from the perspective of working memory and emotional regulation.

This study found that physical fitness was closely related to executive function and social skills, with muscle strength having the strongest correlation to both. The improvement of physical fitness provided a foundation for children's positive adaptive behavior, promoting the occurrence of social behavior and fostering a virtuous cycle of social participation[43,44]. Furthermore, the social behavior of children with ASD was closely related to muscle strength. Motor abilities in children with ASD develop more slowly[45], but actions such as reaching out and grasping facilitate object manipulation and promote joint engagement with objects and caregivers, increasing sensitivity to the interaction of individual, environment, and behavior[22]. Children with ASD communicated more frequently with family, peers, caregivers, and others through vocalizations and gestures, providing opportunities for richer social behaviors (54). Lower limb muscle strength played an important role in children's independent walking, which was associated with changes in perception, cognition, and social development. Moving in an upright posture could create a new relaxed field of view (including distant objects and facial recognition), increasing visual connection to the world and thus promoting social behavior.

Moreover, deficits in motor coordination and social interaction abilities have been linked to the functionality of the mirror neuron system, which plays a key role in action observation, imitation, and understanding the intentions and emotions behind behavior, all integral to executive function[46]. Exercise-induced neuroplasticity extends beyond motor-related brain regions and may contribute to the enhancement of executive functioning[47]. Therefore, given the strong interrelationship between executive function and social interaction abilities, along with the shared neural mechanisms underlying these domains and their connection to health-related physical fitness development, incorporating exercise-based interventions into research focused on improving executive function and social interaction abilities is crucial.

Although this study demonstrated a relationship between physical fitness and executive function as well as social interaction abilities, the current data only shows correlation rather than causation, making it premature to suggest that physical fitness interventions would directly improve executive function or social behavior. Future studies should cautiously explore the potential benefits of such interventions and rely on stronger causal evidence.

Additionally, this study found that overall executive function in children with ASD is impaired, and that executive function is correlated with social skills. However, this finding is inconsistent with previous studies. Potential reasons include: 1.The evaluators were different from those in previous studies; prior studies mainly relied on parental assessments, whereas this study used teacher assessments[48]. Previous research has suggested that maternal control styles may affect how children's executive function is evaluated[49]. Therefore, future studies should consider a multi-method evaluation approach for more comprehensive and accurate assessment of executive functions in ASD children. 2. The classification of executive functions differs[50,51]. This study used the BRIEF scale to assess executive function in school-aged children, which includes two dimensions (behavioral regulation index and metacognitive index) more closely aligned with daily. 3. The participants' ages were different. Previous studies mostly compared executive functions and social skills in preschool children[52], whereas this study examined school-aged children, whose social interactions and activity needs are more complex, which may reveal a more accurate picture of ASD children's developmental characteristics.

4 Research Limitations and Future Directions.

This study used a cross-sectional design, which limits the ability to make causal inferences. Future longitudinal studies could further investigate the interactions between executive function and social interaction deficits proposed in this study. Since this study only included male ASD participants, the generalizability of the findings may be limited. Future studies could include gender comparisons to enhance the generalizability of the results. Furthermore, cognitive indices were not assessed, limiting the explanation of broader developmental relationships. Future research could explore objective assessment methods suitable for children with ASD. Finally, future studies could further investigate the relationships between physical fitness, motor function, executive function, and core symptoms, and attempt to establish exercise intervention programs based on physical fitness to support improving core symptoms of ASD through physical activity.

5 Conclusions.

In conclusion, considering the strong interrelationship between executive function and social interaction abilities, along with their shared potential mechanisms and connection to physical fitness development, this study emphasizes the importance of incorporating exercise-based interventions into research aimed at improving executive function and social interaction abilities. Exercise interventions can not only improve physical health in children with ASD, but also promote social behavior and cognitive development, holding significant clinical application potential.

Data availability

The findings of this study will be supported by data provided upon request by the study sponsor, Shanghai Sport University. In accordance with specific standards, conditions, and exceptions, relevant de-identified personal data of participants may also be provided by Shanghai Sport University. Additional information may be obtained by contacting Shanghai Sport University. Enquiries may also be directed to the corresponding author.

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Author contributions

Q.W., S.J., and J.W.: conception, design, and revision of the article. Z.C. and W.J.: conducted the study and edited the article. Q.W., S.J., Z.C., X.W. and W.J.: data acquisition and analysis. S.J. and Q.W.: wrote the manuscript. All authors contributed to the article and approved the submitted version.

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Declarations

Competing interests

The authors declare no competing interests.

Ethics approval

This study has been approved by the Ethics Committee of Shanghai University of Sport (102772020RT061). All subjects signed an informed consent form indicating their consent to participate in the study.

Consent for publication

No conflict of interest exits in the submission of this manuscript, and manuscript is approved by all authors for publication.

Additional information

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