Trials

STUDY PROTOCOL

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The effect of diverse sports skills interventions on physical fitness and brain development among Chinese high school students: a cluster randomized controlled trial study protocol

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Abstract

Background During adolescence, research concerning physical fitness and brain development has become a focal point in health and neuroscience. Academic debates on the precise impact of different sports skills on adolescent physical fitness lack consensus. While exercise's positive effects on brain development in children and older adults are well-documented, its specific impact on adolescents remains unexplored. A year-long trial explores how diverse sports skills affect adolescents' physical fitness and brain development. The study has a dual focus: first, to examine the potential correlation between sports skills acquisition and indicators of adolescent physical fitness; and second, to investigate the mechanisms of brain plasticity in adolescents. This comprehensive study is poised to fill knowledge gaps, providing a scientific basis for targeted health interventions in adolescent populations.

Methods This study will employ a randomized controlled cluster design involving senior high school students in Shanghai. The expected sample size is approximately 450 students, divided into four experimental groups and a control group. The experimental groups will undergo 1 year of sports skills training in basketball, football, tennis, and martial arts, while the control group will receive regular physical education classes. Prior to intervention, data will be collected on students' physical fitness, sports skills, levels of physical activity, and functional magnetic resonance imaging (fMRI) measurements. Rigorous control of variables will ensure comparability and experimental validity. For data analysis, specialized software tools, including SPSS 18.0, AMOS 18.0, Matlab R2013b, and EXCEL, will be employed for comprehensive analysis and interpretation, validating potential differences between experimental and control groups in various aspects of physical fitness and sports skills.

Discussion This experiment aims to provide substantial scientific evidence on the impact of sports skills learning on diverse indicators of adolescent physical fitness. In addition, it aims to elucidate the effects of exercise on adolescent brain plasticity and its specific underlying mechanisms. This comprehensive evidence base is poised to serve

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as a basis for more effective interventions in the future, providing enhanced scientific guidance for promoting holistic adolescent development. It also provides scholars and practitioners with fresh perspectives on adolescent health development.

Trial registration The study was registered at the China Clinical Trial Registry (ChiCTR2300070942). https://www.chictr.org.cn. Registered on April 10, 2023

Keywords Sports skills, Physical fitness, Brain, Youth, Health promotion

Administrative information

Note: the numbers in curly brackets in this protocol refer to SPIRIT checklist item numbers. The order of the items has been modified to group similar items (see http://www.equator-network.org/reporting-guidelines/spirit-2013-statement-defining-standard-protocol-items-for-clinical-trials/).

Title {1}	The effect of diverse sports skills interventions on physical fitness and brain development among Chinese high school students: a cluster randomized controlled trial study protocol
Trial registration {2a and 2b}	Ethical clearance has been obtained from the Institutional Review Board (IRB) of the Shanghai University of Sport (102772022RT031). The trial is registered at the China Clinical Trial Registry (ChiCTR2300070942).
Protocol version {3}	Protocol version 02 (5/10/2023)
Funding {4}	Program for Overseas High-level Talents at Shanghai Institutions of Higher Learning (TP2022102) and the Research and Innovation Grant for Graduate Students (Shanghai University of Sport Project No. YJSCX-2023–012)
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Name and contact information for the trial sponsor {5b}	Yang Liu, Shanghai University of Sport, School of Physical Education; Shanghai University of Sport, Shanghai Research Center for Physical Fitness and Health of Children and Adolescents; Physical Education National Experimental Teaching Demonstration Center, Shanghai University of Sport, 650 Qingyuanhuan Road, 200,438, China Email: docliuyang@hotmail.com
Role of sponsor {5c}	The sponsor maintains authority over all aspects of the trial including design, management, interpretation of results, and publication.

Introduction

Background and rationale {6a}

Physical fitness, as a comprehensive reflection of an individual's overall health, encompasses various physiological, psychological, and social characteristics. It includes multidimensional features such as body morphology, physiological functions, psychological qualities, and adaptability, all of which are influenced by genetic and environmental factors [1–3]. Maintaining and promoting physical fitness is critical to an individual's overall well-being, including factors such as cardiovascular health, mental health, immune function, musculoskeletal health, and reducing the risk of chronic diseases [4–6]. However, current research suggests that the state of physical fitness among adolescents worldwide is generally concerning [7–10]. Urgent action is needed to address this issue and to maintain and promote adolescent physical fitness. Research has shown that the adolescent period is a critical time for shaping an individual's physical fitness and sports skills. Studies emphasize the importance of enhancing sports skills acquisition during adolescence, contributing to improved physical fitness levels during adolescence and adulthood [11–13]. It is particularly noteworthy that adolescents with lower sports skills are more likely to develop overweight or obesity, a trend that may persist into adulthood [14, 15]. Therefore, mastering sports skills during adolescence is of paramount importance. However, the diverse effects of different types of sports skills on various aspects of adolescent physical fitness have not yet received sufficient research and

understanding, warranting further in-depth investigations to fully grasp the multidimensional characteristics of adolescent physical fitness.

A substantial body of research has unequivocally demonstrated that sports skills acquisition has profound and enduring effects on individual brain structure and function [16–18]. Moreover, a growing body of evidence suggests that sports skills learning plays a pivotal role in enhancing neuro-sports function and promoting adaptive plasticity within brain motor circuits [19, 20]. Brain remodeling is a complex process involving dynamic changes at both physical and physiological levels of the brain, encompassing alterations at molecular, cellular, and systemic levels. Research has shown that sports skills learning can stimulate neuronal growth and synapse formation while simultaneously strengthening connections between different brain regions [21, 22]. These neurophysiological changes are of paramount importance in enhancing an individual's cognitive abilities, including improvements in learning, memory, problem-solving, and decision-making. A growing number of randomized controlled trials further highlight the causal relationship between sports skills learning and the plasticity of adolescent brain structure and functional activity. It is worth noting that both long- and short-term exercise interventions have been shown to promote brain plasticity. While the association between sports skills learning and cognitive development in adolescents has gained increasing scholarly interest, it should be emphasized that some studies suggest that the cognitive benefits of exercise may be more pronounced in children and older adults. Consequently, there is still debate about the precise impact of sports skills learning on the adolescent population [23]. Several constraints inherent in these investigations, including limited sample sizes and variability in exercise intervention dosage, have the potential to contribute to incongruous research outcomes [24–26]. However, despite these occasional differences, the current research consensus highlights the beneficial impact of sports skills learning on both the function and structure of the adolescent brain. The advent of functional magnetic resonance imaging (fMRI), which combines neural activity with high-resolution imaging, provides a quantitative and spatial means of assessing brain activity during the execution of various perceptual, motor, and cognitive tasks. It has become a crucial advanced technology for investigating the mechanisms by which exercise affects the brain. This is also one of the technical approaches used in our study. To thoroughly investigate the intricate interactions and relationships between sports skills learning and the complex network of brain structure and functional connectivity, including exploring how sports skills learning synchronously influences brain morphological development, long-term follow-up studies are essential. Such research efforts will contribute to a more comprehensive understanding of the mechanisms by which sports skills learning affects the adolescent brain, thus providing a deeper and scientifically grounded basis for the development of intervention strategies.

Specialized sports skills in the field of physical education are clearly defined as the ability to acquire highly specialized techniques, movements, rules, and tactics required for specific sports through systematic and long-term training [27, 28]. Adolescence is widely recognized as a critical developmental stage for mastering specialized sports skills [29]. Moreover, it is a period that has a lasting impact on an individual's health [30]. School environments are considered ideal places to promote sports skills learning among adolescents because schools provide essential resources such as equipment, personnel, facilities, and curricula designed to encourage and provide opportunities for sports skills learning [31, 32]. It is worth emphasizing that a significant portion of adolescents' waking hours are spent in the school environment. In addition, adolescence is considered a pivotal and sensitive period for enhancing physical fitness, refining physical abilities, nurturing physical health, and harnessing brain plasticity. Adolescence is also an integral part of a broader educational framework. There is substantial evidence that mastering sports skills has positive effects on physical fitness and brain structure throughout an individual's life span [33–35]. However, several critical questions remain: What are the effects of different types of specialized sports skills on adolescents' physical fitness and brain structure? What are the underlying mechanisms by which sports skills affect adolescent physical fitness and brain structure? These questions require validation through the implementation of long-term follow-up studies. In China, high schools have implemented specialized sports skills education, providing adolescents with the opportunity to continue learning sports skills throughout their 3-year physical education curriculum. Therefore, this study will analyze the effects of long-term sports skills acquisition on physical fitness and brain development in adolescents.

Objectives {7}

Through a long-term randomized controlled trial involving diverse sports skills learning interventions, this study will investigate the effect of sports skills learning on adolescent physical fitness, to provide specific and robust scientific evidence to enhance overall well-being. In addition, the study will analyze the effects of diverse sports skills learning on adolescents' brains, exploring mechanisms to enrich the theoretical understanding of the impact of sports skills on adolescent brain plasticity.

Ultimately, this work lays a solid theoretical and practical foundation for the promotion of comprehensive adolescent development, thus fostering their overall well-being.

Trial design {8}

This is a randomized controlled trial designed based on a superiority framework, aiming to determine whether specialized motor skills training in physical education classes results in superior outcomes in physical fitness and brain development compared to regular physical education classes. The study consists of an intervention group (specialized motor skills training, divided into four subgroups: basketball, football, tennis, and martial arts for 1 year) and a control group (regular physical education lessons without specialized motor skills). The primary hypothesis is that specialized motor skills training will result in significantly better physical fitness and brain development outcomes compared to the control group. The trial follows the SPIRIT [36] (Fig. 1) (Standard Protocol Items: Recommendations for Interventional Trials) checklist (Additional file 1), and the flowchart of the trial is shown in Fig. 2. The superiority framework will guide the statistical analysis, with the null hypothesis (H0) being that there is no significant difference between the intervention and control groups, and the alternative hypothesis (H1) being that the intervention group demonstrates superior outcomes.

Methods: participants, interventions and outcomes

Study setting {9}

Participating schools were organized into clusters based on their geographical location within specific school districts, mainly high schools. Data collection took place at three distinct time points: baseline (during the autumn of the first academic year), mid-term test (following 6 months of intervention), and post-test (conducted 1 year of intervention).

Eligibility criteria {10}

To be eligible for participation in this study, participants are required to meet the following criteria: (1) right-handedness: participants have to be right-handed children, as prior research has suggested that brain measures may differ between left- and right-handed individuals [37]; (2) normal vision or corrected vision: eligible participants need to have normal vision or vision that could be corrected, and should not exhibit color blindness or color weakness; (3) good health: all subjects are required to be in good health, devoid of any history of brain injury, drug dependence, mental health disorders, neurological conditions, or relevant family history; (4) absence of metal implants: participants should not have any metal implants or other implants within their bodies; (5) informed consent: before participation, participants will receive comprehensive explanations about the scanning process, the study's objectives, significance, and safety procedures. Students who willingly agreed to partake in the study will be required to sign an informed consent form, and the parental informed consent form will be provided to legal guardians for their signature.

Participants will be excluded if: (1) the body contains ferromagnetic implants such as magnetic metal dentures, arterial clips, steel wires, metal-free artificial heart valves, artificial cochlea, electronic ears, in vivo syringes, in vivo electrodes, or nerve stimulators; (2) have a history of neurological or mental illness; (3) nonnative Chinese speakers; (4) people suffering from major physical diseases (such as cardiovascular, cerebrovascular, liver, and kidney diseases); (5) suffer from congenital diseases or growth retardation and symptoms or chronic diseases that seriously affect participation in sports.

Who will take informed consent? {26a}

The investigators (MHB, XLQ) will obtain informed written consent from participants after explaining the potential benefits and risks of participation and the right to withdraw from the study.

Additional consent provisions for collection and use of participant data and biological specimens {26b}

Informed consent has details of the tests to be conducted and the data collected will not be reused outside of this study, this study does not involve biological specimens from the participants, therefore no further consent will be obtained from the participants.

Interventions

Explanation for the choice of comparators {6b}

Studies have shown that sports skills learning has a beneficial promotion effect on adolescent physical fitness and brain development, but the effects of diverse sports skills learning on various indicators of adolescent physical fitness are unclear, and the mechanisms of different sports skills on adolescent brain plasticity need to be further explored. Therefore, it is important to investigate the effects of diverse sports skills learning interventions on the physical fitness and brain development of adolescents to help promote the healthy and comprehensive development of adolescents.

Intervention description {11a}

In this study, 15-year-olds (10th grade) will be recruited from both public and private schools in Shanghai, China. The recruitment drive takes place between

	STUDY PERIOD				
	Enrolment		Allocation	Post-allocation	
TIMEPOINT	$-T_1$	0	T_1	T_2	T_3
ENROLMENT:					
School Eligibility Screen	X				
Headteacher Consent	X				
Teacher Consent	X				
Parental opt-out consent	X				
Pupil Assent	X				
Randomization		X			
INTERVENTIONS:					
Football skill			←	—	→
Basketball skill			←	—	→
Tennis skill			←	—	→
Martial arts			←	—	→
PE as usual (Control)			←	—	→
ASSESSMENTS:					
Sociodemographic data			X	X	X
Physical fitness			X	X	X
Sports skill			X	X	X
Brain health			X	X	X
Physical activity			X	X	X

Fig. 1 Standard Protocol Items: Recommendations for Interventional Trials (SPIRIT)

September 2023 and March 2024, using social media platforms and banners as recruitment channels. The enrolled high school students will be classified into five distinct groups: four intervention groups and one control group, based on their choice of specific skills. These groups include (1) football skill intervention group (group A), (2) basketball skill intervention group (group B), (3) tennis skill intervention group (group C), and (4) martial arts skill intervention group (group D). (5) The control group will receive standard physical education instruction without systematic specialized sports skills training (group E). The entire experiment consists of three distinct phases: pretest, mid-test, and post-test. Consistency will be maintained across these phases in terms of locations, measurement tools, test timing, examiners, and test protocols. The intervention

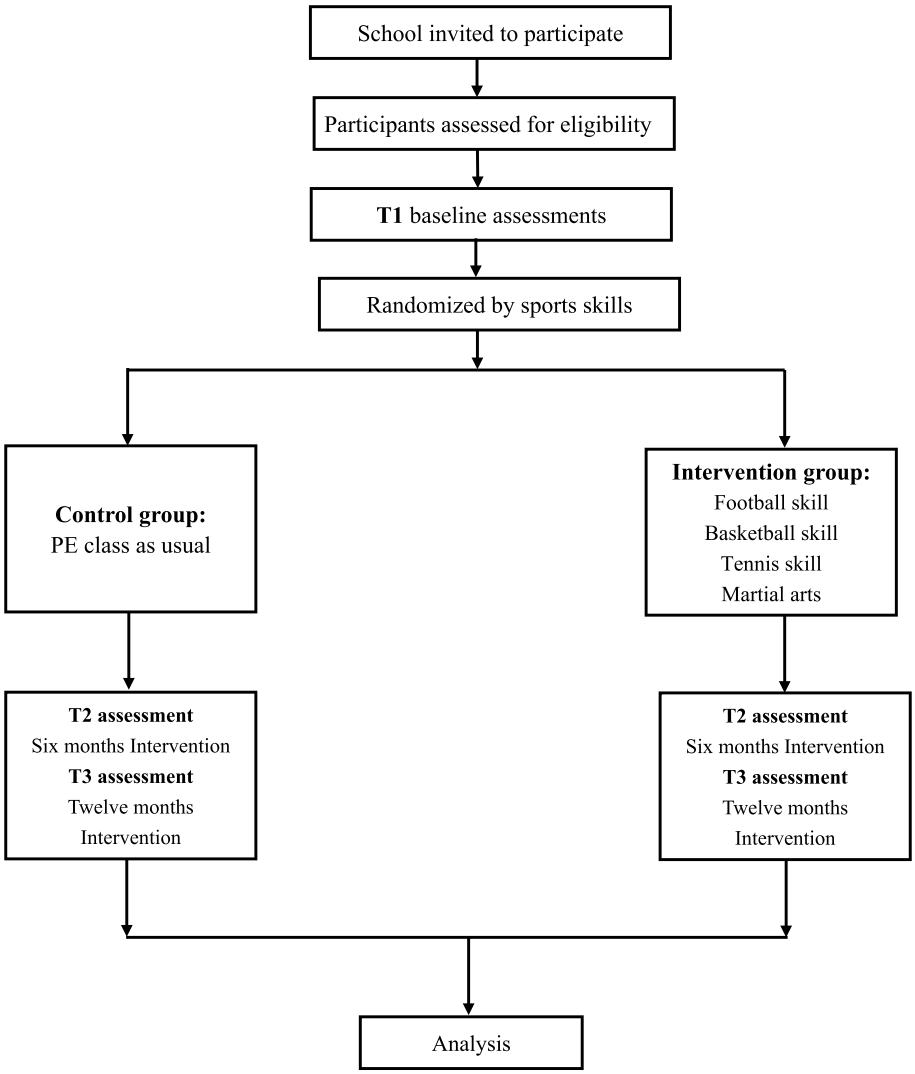

Fig. 2 Study design and flow

group will participate in 80-min specialized instruction sessions twice a week, conducted in small-class settings with an average of about 25 participants. This schedule translates into four class hours per week, amounting to a total of 144 class hours over the 1-year intervention period. In contrast, the control group will receive standard physical education instruction during the same period. The selection of intervention activities will be made with due regard to the nature of the projects. Specifically, interventions included basketball and football in the same large-ball category, tennis in the small-ball category, and martial arts as a representative of traditional national sports. These choices are made to ensure a comprehensive and well-balanced intervention program.

To mitigate the potential impact of specialized sports skills acquisition on the skill level and physical fitness of control group students, the control group will participate in regular physical education classes, while the intervention group will receive specialized training in four distinct skills. In the context of this study, "regular physical education" was defined as (1) students do not engage in systematic training for specialized sports skills; (2) proficiency in specialized sports skills is not part of the performance assessment in the physical education curriculum. In addition, the control group's physical activity levels are monitored weekly by their teachers to ensure that they meet the intervention plan requirements.

Criteria for discontinuing or modifying allocated interventions {11b}

Participants will be withdrawn from the study and receive appropriate treatment in the event of an injury, illness, or

other unforeseen circumstance during the physical education program as well as in the student's regular life. Participants may withdraw from the study at any time for any reason.

Strategies to improve adherence to interventions {11c}

Before the official start of the intervention, a seminar and pilot study will be held for all intervention personnel to verify the intervention content of the interveners and the feasibility of the intervention plan. The formal special skills intervention will be implemented by the school teachers participating in this study. Teachers will receive relevant training before the intervention, and the training will be conducted through prepared intervention combinations, demonstrations, and visual materials. After the training, the researchers will conduct guided interviews to obtain the following relevant information: (1) using methods and materials, combined with the characteristics of high school students, to obtain information on teaching and mediation skills; (2) whether the intervener will implement the intervention as planned; and (3) any comments and general comments on training improvements.

In the pilot study, each participant will conduct a special sports skills intervention course according to groups and use the checklist provided by the researchers to provide feedback on the feasibility of the course according to different standards (time, content, objectives, etc.). Each intervention group will assign an additional investigator to monitor the quality of the intervention. In addition, researchers will also play a protective role by recording any special circumstances (accidental injuries) that occur during the intervention. To ensure the effectiveness of the experiment and minimize potential errors, pre-test, mid-test, and post-test evaluations will be completed within 1 week. To mitigate the "Hawthorne" effect during the experiment, measures will be taken to maintain consistency across various aspects. This included matching the number of students, structuring teaching arrangements, harmonizing teaching content, and standardizing teaching hours for the same intervention project wherever feasible.

Throughout the experiment, careful control measures will be implemented to ensure accurate management of exercise duration and intensity. Pulse measurements will be obtained by palpating the flexor artery or common carotid artery. Typically, post-exercise heart rate measurements will be calculated by determining the heart rate over a 10-s interval and then multiplying it by 6. This calculation method will be used because of the rapid recovery of heart rate after exercise, allowing an accurate reflection of the maximum heart rate achieved during physical activity.

Relevant concomitant care permitted or prohibited during the trial {11d}

Participants in the intervention group will, in principle, receive no additional skills training for the duration of the intervention, and students in the control group will receive no extracurricular or club-based skills training in addition to their physical education program. Participants in both the intervention and control groups will follow their usual routines and the intervention will not change their lifestyles. Participant attendance should also be guaranteed, and test results for participants who have been absent from classes more than three times should be eliminated.

Provisions for post-trial care {30}

The risk of injury associated with the intervention content in this study is low, and injury events are rarely reported in similar studies. During the implementation process, unless the injured student affects the intervention or other irresistible factors, the intervention will continue as planned. Intervention and data analysis will be based on the intent of treatment analysis. Data from all registered participants will be analyzed; missing data will be processed using the mean interpolation method. If a student is injured during the course, the school, parents, and the person in charge of the study will jointly negotiate the treatment plan.

Outcomes {12}

Primary outcome measures

This study has three primary outcomes, which are assessed at three time points: baseline (0 months), mid-test (6 months), and post-test (12 months). These primary outcomes are as follows.

Physical fitness The primary outcome of the study is physical fitness, which is defined as the body's ability to perform optimally in response to physiological stress and is manifested through six attributes: cardiorespiratory fitness (CRF), muscular strength, speed, agility, flexibility, and body composition [38]. We will use the Chinese National Student Physical Fitness and Health Standard, a field-based test battery, to assess each student's physical fitness (Table 1). Assessments included vital capacity for bodily functions, sit-and-reach for flexibility, standing long jump for lower limb strength, pull-up and handgrip for upper limb strength, a 50-m run for speed, 1000-m/800-m run, and a 20-m multistage shuttle run (20 m MSR) for cardiopulmonary endurance. It is worth noting that the 20 m MSR and handgrip are two test

Table 1 Physical fitness tests

PF	Test	Materials	Directions	Performance criteria
Body morphology	Height	Height gauge	The subject stood barefoot and upright on the bottom panel of the altimeter. The heel, sacrum, and scapula areas are in contact with the column, the trunk is naturally straight, and the head is upright	The tester stands on the right side of the subject and slides the horizontal pressure plate down the column and gently presses it against the top of the subject's head. Both eyes should be read at the same height as the platen level. Test results are measured in centimeters and are accurate to one decimal place
	Weight	Scale	The subjects were barefoot, the male subjects were wearing shorts, and the female subjects were wearing shorts and short-sleeved shirts, standing in the center of the weighing table	Reads in kilograms, accurate to one decimal place
Body functions	Vital capacity	Spirometer	The subject stood facing the instrument and tried to blow 1 to 2 times with the mouthpiece in hand. Hold your breath after taking a deep breath and exhale as deeply as possible with your mouth, blowing with full force at medium speed and force until you cannot exhale. Do not inhale twice during the test	After the blowing is completed, the final number displayed on the LCD screen is the spirometry milliliter value. The subjects tested three times, each time with an interval of 15 s, recorded the value three times, and selected the maximum value as the test result. In milliliters, no decimals are retained
Flexibility	Sit-and-reach	Sit-and-reach device	The subject sits barefoot, legs straight, feet apart about 10 to 15 cm flat pedal to the footboard, upper body forward flexion, arms straight forward, with the fingertips of both hands gradually pushed forward until it cannot be pushed forward	The test gauge is 0 points along the plane inside the footboard, the negative value is negative if it does not reach 0 points, and the value is positive if it exceeds 0 points. Records are recorded in centimeters, retaining one decimal place. Each person takes the test twice to get the best score
Lower limbs strength	Standing long jump	Standing long jump mat	The subject naturally stands on two feet apart, standing behind the jumper, and the tip of the foot must not step on the line. Both feet take off and jump at the same time, and there must be no cushion steps or continuous jumping movements	Each person tries to jump three times and records the best of them. In meters, two decimal places are reserved
Upper limbs strength	Pull-up	Horizontal bar	Subjects face horizontal bars and stand naturally; then jump up the forehand to hold the bar, the hands are separated and shoulder width, the body is in a straight arm hanging posture, after the body stops shaking, both arms at the same time, pull-up; the body must not make any additional movements during pull-ups	When the lower jaw exceeds the upper edge of the horizontal bar, it is reduced to a straight arm overhang posture and completed once. Record the number of times a subject completed. In second orders
Speed	50-m run	Athletics field 50-m running track	Subjects are tested in groups of at least two people. Stand-up start, the subject hears the "run" password and starts running. The commander swings the starting flag while issuing the order	The timer starts the timer according to the flag movement, and the subject's torso position reaches the vertical surface of the finish line to stop the meter. Test results are recorded in seconds, accurate to one decimal place, and the second digit after the decimal point is entered as a non-"0", such as 10.11 s and 10.2 s

Table 1 (continued)

PF	Test	Materials	Directions	Performance criteria
Cardiopulmonary endurance	1000-m/800-m run	Athletics field	Subjects are tested in groups of at least two people. Stand-up start, the subject hears the "run" password and starts running	The timekeeper sees the flag movement and starts the timer, stopping the watch when the subject's torso reaches the vertical surface of the finish line. Test results are recorded in minutes and seconds, regardless of decimals
Cardiopulmonary endurance	20-m shuttle run	Athletics field, markers, speakers	Subjects, between two markers 20 m apart, performed an intermittent turnback run at an increasing speed, changing direction at the speed set by the audio signal, which gradually sped up	The test stops when the subject is unable to reach the set audio signal or when fatigue is unable to continue. Record the number of times a subject completed
Upper limbs strength	Handgrip	Grip force meter	The subject's feet are naturally separated into an upright position, the arms are naturally drooping, and the grip is fully clenched with a powerful handheld grip gauge	Reads in kilograms, accurate to one decimal place. Hold 2 times, taking the maximum value

items added to the Chinese national students' physical fitness and health standards. 20 m MSR is strongly correlated with peak oxygen consumption and is widely used as an indicator of CRF in youth [39]. In addition, we will measure height and weight to calculate age- and gender-adjusted BMI and BMI *z*-score, following standards recommended by the International Task Force on Obesity [40].

Specialized sports skills In pursuit of assessing students' achievement in specialized sports skills, the "Youth Sports Skill Level Standard" developed by the research team at Shanghai University of Sport is employed to measure students' performance in level 3 sports skills. The Youth Sports Skill Level Standard was collaboratively developed by authoritative experts convened by the Shanghai University of Sport. Through rigorous testing involving over 9000 young adolescents and numerous rounds of expert discussions, a comprehensive system was established. This system comprises a four-level, twelve-grade hierarchical structure for 11 different sports. Notably, it gained endorsement from China's education department and underwent verification by the quality inspection department. Consequently, a unified quantitative standard was formulated for assessing the skill levels of youth in sports across China. A total of four components were evaluated. Please refer to the tables and figures for specific test procedures for football (Table 2 and Fig. 3), basketball (Table 3 and Fig. 4), and tennis (Table 4). The assessment of martial arts will be based on the execution of Shaolin Eight Step Interlink Quan, consisting of two sections performed with eight steps, seven fist techniques, three palm techniques, four leg techniques, two catch techniques, one defensive position, one ready position, and two repeating positions. Evaluators will rate students based on their on-site performance, and those who achieve a score of 7.8 or higher will be considered qualified.

Functional magnetic resonance imaging (fMRI) In the current study, brain plasticity is operationalized through functional magnetic resonance imaging (fMRI). The images will be acquired using a Siemens Magnetom Trio 3.0 T magnetic resonance imaging device, which is provided by the Shanghai University of Sport. Subjects will be securely immobilized to minimize head and body movement, ensuring they remain awake and with their eyes closed. Prior to each fMRI scan, participants underwent a 10-min rest period in a quiet and comfortable environment. Subsequently, the subjects' resting heart rate was measured, with a requirement that the heart rate be below 85 beats per minute to confirm their restfulness. To assess brain plasticity, resting-state functional magnetic resonance data (RS fMRI) were collected using fast gradient echo imaging with high-precision three-dimensional magnetization. The imaging parameters are as follows: repetition time = 3130 ms, echo time = 2.98 ms, inversion time = 450 ms, flip angle = 12°, and field of view = 25.6 cm^2. The data will be analyzed to examine changes in functional connectivity and network-level reorganization within the brain. Specifically, we will use seed-based correlation analysis and independent component analysis (ICA) to identify changes in functional connectivity associated with key brain regions involved in motor control, cognitive function, and emotional regulation, such as the motor cortex, prefrontal cortex, and hippocampus. In addition to functional connectivity analysis, graph theory-based metrics—including global efficiency, local efficiency, and modularity—will be calculated to explore alterations in brain network topology. These metrics have been widely used in neuroimaging studies to quantify brain plasticity, as they provide a measure of the brain's ability to reorganize and adapt to interventions. Furthermore, amplitude of low-frequency fluctuations (ALFF) and regional homogeneity (ReHo) will be assessed to examine local neural activity changes, which reflect the functional adaptability of the brain.

Secondary outcome measures

Physical activity We will objectively measure adolescents' physical activity (PA) using ActiGraph accelerometers (model wGT3X-BT). Adolescents will wear these accelerometers on the left side of their waist continuously for a full week, covering 5 weekdays and 2 weekend days. They can remove accelerometers when going to bed, bathing, or engaging in water activities. Before data collection, a research staff member will explain the purpose of accelerometers and provide instructions to teachers, parents, and children on their use and care. The devices will be set up to collect data at 30 Hz and record activity in 3-s epochs [42].

For the subjective assessment of physical activity, we will use the International Physical Activity Questionnaire Short Form (IPAQ-SF). The IPAQ is the most widely used physical activity questionnaire [43]. The 9-item short form (IPAQ-SF) assesses activity across four intensity levels: (1) vigorous activity, (2) moderate-intensity activity, (3) walking, and (4) sitting [44]. It is widely recognized for its reliability and validity [45]. Teenagers will be asked

Table 2 Football tests [41]

Test	Directions	Cautions	Compliance standard	Site layouts
Quick dribbling	The participant places the ball on the starting line, raises hand to signal readiness to the examiner, upon confirmation from the examiner, begins dribbling the ball forward. Timing commences as the ball departs from the starting line	Prior to the commencement of the test, no part of the participant's body is allowed to cross over the starting line	Boys complete the test within 9 s, girls complete the test within 12 s	The exit of short pass area is 4 m away from the sign post ①, ① away ② 1 m, ② away ③ 3 m, ③ away ④ 1 m, ④ away ⑤ 3 m, ⑤ away ⑥ 3 m
Short-range passing and receiving	Quick straight-line dribble to the short-passing area, pass the ball to wall 1 or 2 within the short-passing area, completing a short-range passing and receiving drill	1. The subjects must enter from the entrance of the short-passing area 2. If the ball kicked out does not make contact with the wall (kicked away), the test will fail 3. If the ball rebounds off the wall and stops between the wall and the short-passing area, the participant should bring the ball back to the short-passing area and reattempt the passing and receiving drill		
Dribble through obstacles	Receive the rebounded ball from wall 1 or 2, dribble forward out of the short-passing area exit, and continuously dribble around the poles starting from either side of marker pole ①	The participant must dribble the ball from the short-passing area's exit without missing markers or colliding with the pole. If there is an error, the ball should be returned, and the test restarted from the point of error		
Shooting	After dribbling around the pole, shoot the ball toward the goal area from the penalty area line	1. The moment the ball crosses the line, the clock stops and the test is finished 2. If the ball rebounds into the goal from the inside of the goal frame, the result is valid 3. If the ball is kicked out of the goal or hits the goal frame and rebounds inside or outside the field, the result is invalid		

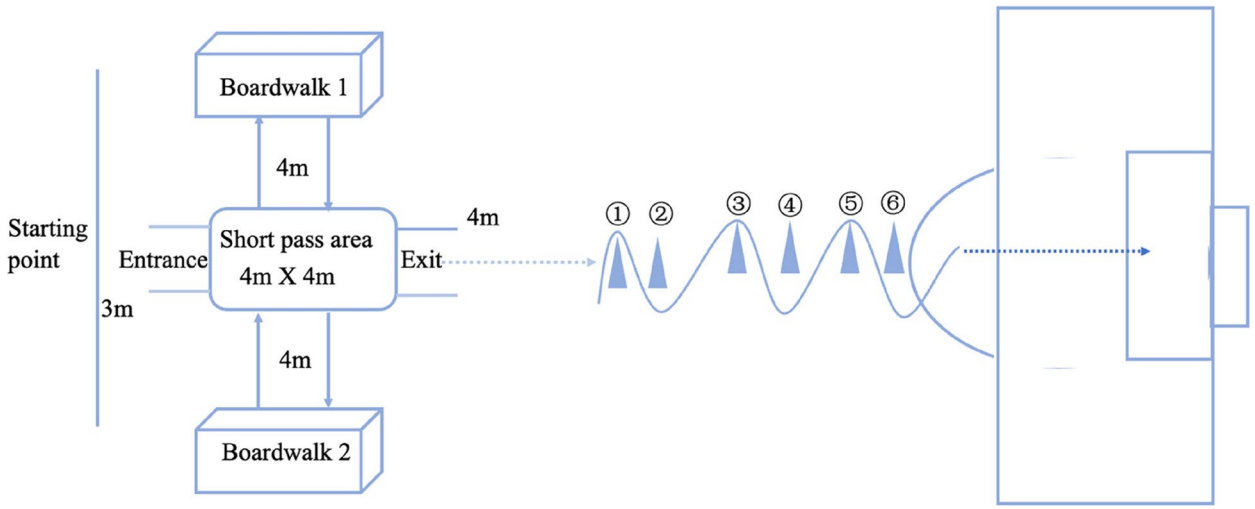

Fig. 3 Football test diagram

to self-report their physical activity over the previous 7 days, and they completed the questionnaire themselves.

Descriptive measures The descriptive indicators of this study are (1) sociodemographic characteristics and (2) anthropometric data, including height, weight, and body mass index (BMI). Standing height will be measured barefoot using a stable stadiometer (GMCS-SGZG3, Jian-Min, Beijing) to the nearest 0.001 m. Body weight with light clothing will be measured using a portable scale (GMCS-YERCS3, Jian-Min, Beijing) to the nearest 0.1 kg (kg). BMI will be calculated by height and body weight.

Participant timeline {13}

The study will assess primary and secondary outcome measures and descriptive data over three periods. Participants will be assessed at baseline, mid-term test, and the end of the intervention. During each assessment, which takes place within a week, we will measure participants' specialized sports skills, physical fitness, physical activity, and brain structure by scanning and collecting descriptive data (such as age, gender, weight, and height). Test results will be promptly recorded to ensure comprehensive data collection. Any data anomalies detected on the same day will be addressed with additional tests the following day. And project testers remain consistent throughout. To minimize participant attrition, researchers will inform teachers of measurement details before the assessment begins, facilitating communication to reduce participant loss. Details of the study schedule are given in Fig. 1.

Sample size {14}

The design of this study uses cluster random sampling, using a repeat measurement approach with 5 arms and 3 time points. To ensure that significant changes occur from baseline to the point in time after intervention, a priori power analysis was performed using G*Power 3.1. The analysis involved calculating the total scores of 10 physical fitness measures (including height, weight, BMI, vital capacity, 50-m running, sitting forward-leaning, standing long jump, long-distance running, upper limb waist and abdomen strength), 4 sports skills (football, basketball, tennis, martial arts), and brain structure scores derived from fMRI data. Assuming a power of 80% and a significant level of 0.05, and considering the effect sizes observed in previous research on intervention effects on physical health and brain structure [46, 47], the effect sizes were conservatively set at a medium level (0.25). The required sample size was determined to be 125. To account for the design effect of cluster randomization, the cluster sample size (m) was expanded using the formula: $M = M' * (1 + ICC * (M' - 1))$, where M is the number of people in each cluster, M' is the non-cluster sample size, and ICC is the intra-group correlation coefficient. For interventions involving students, ICC values typically fall between 0.02 and 0.1 [48–50]. A conservative ICC estimate of 0.05 was chosen to enhance the robustness of the research [51, 52]. Assuming an average class size of 45, the cluster sample size was estimated to be 360. In addition, a dropout rate of approximately 15% was assumed for potential participants, resulting in a total sample size of 450.

Table 3 Basketball tests [41]

Test	Directions	Cautions	Compliance standard	Site layouts
Crossover dribble layup	(1) After hearing the official's timing whistle, the participant starts from the right sideline behind the midline, dribbles with the left hand to obstacle ①, performs a crossover dribble (2) Drive with the right-hand dribble for a layup; if the layup is missed, follow up for a rebound until a successful basket is made (3) After securing the rebound, dribble with the right hand to the left midline. Upon turning, continue dribbling with the right hand toward obstacle ②, executing a crossover dribble. After grabbing the rebound, dribble past the starting point and the test finished (4) Dribble with the left hand for a layup; if the layup is missed, follow up for a rebound until a successful basket is made (5) After grabbing the rebound, dribble past the starting point. The examiner stops the timing, completing the test	1. The participant must follow the designated route 2. There are no restrictions on using the left- or right-hand during follow-up shots, and both high and low shots are allowed during shooting	Boys complete the test in less than or equal to 19.08 s, girls complete the test in less than or equal to 21.27 s	Standard basketball court

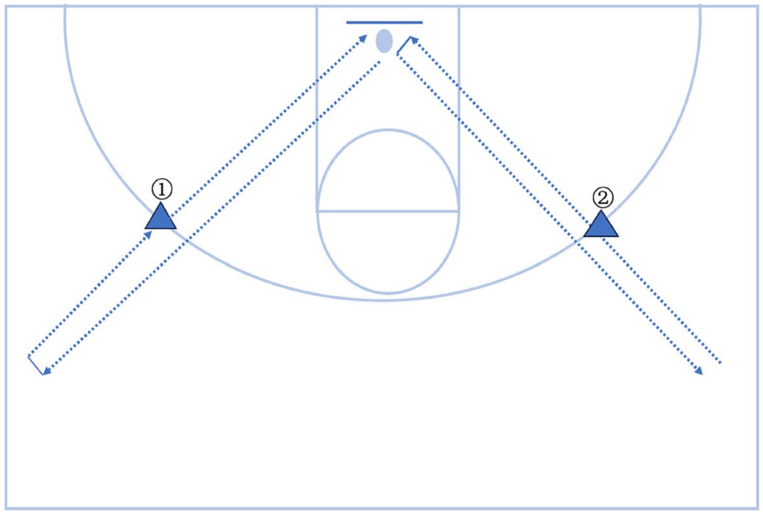

Fig. 4 Basketball test diagram

Recruitment {15}

The study began by collecting information from recruited high school students, including their class names and the number of classes. Students were then assigned to one of the five groups according to their circumstances, following a thorough screening process based on established inclusion and exclusion criteria. Specifically, students were grouped based on their baseline physical fitness levels and availability to participate in the interventions. This stratified grouping ensures that participants are distributed evenly across the groups to minimize differences in baseline characteristics. The five groups include four intervention groups, each focusing on a specific type of diverse sports skills training, and one control group that follows their usual physical education curriculum without additional interventions. This grouping process was conducted by independent researchers to ensure objectivity.

Participants in the study were informed about the study verbally and in writing in their mother tongue. The information provided included the purpose of the study, participant responsibilities, follow-up visits and procedures, potential personal and societal benefits, risks involved, and the ability to withdraw from the study at any time without consequences. To reduce bias, participant blinding was implemented to the extent possible in this type of intervention study. Specifically, participants were not informed of the specific hypotheses being tested or the differences in expected outcomes among the groups. While it was not feasible to completely blind participants to the type of intervention, they were receiving due to the nature of the physical activity interventions, efforts were made to minimize any influence of expectations by standardizing instructions and ensuring all participants were told that each group was part of a broader effort to improve physical fitness and brain health. Additionally, outcome assessors (e.g., those conducting fMRI scans and analyzing results) were blinded to the participants' group assignments to prevent observer bias.

Assignment of interventions: allocation

Sequence generation {16a}

The allocation sequence will be generated using a computer-based random number generator by an independent researcher, who will not be involved in the recruitment process. This ensures unbiased randomization. The group assignments will be concealed using sealed opaque envelopes, each containing a unique allocation corresponding to the random number. The envelopes will be sequentially numbered, and participants will be assigned to one of the five groups (four intervention groups and one control group) based on the order of enrollment. The envelopes will only be opened after the participant's enrollment and consent, preventing prior knowledge of group assignments.

Concealment mechanism {16b}

To prevent any bias, the allocation concealment will be ensured through the use of sealed opaque envelopes containing the random group assignments. The envelopes will remain unopened until after each participant has been enrolled and consented. This process guarantees that neither the researchers nor the participants know the group assignments in advance, minimizing the risk of selection bias. The allocation process will remain concealed throughout the study, with participants and

Table 4 Tennis tests [41]

Test	Directions	Cautions	Compliance standard	Site layouts
Baseline drop shot	Assisted by the examiner standing at the T-mark on the service line, the participant, positioned 3 m behind the service line, aims to hit 5 forehand and 5 backhand groundstrokes, totaling 10 shots. A shot is deemed valid if it clears the net into the singles court	Backhand shots must be executed without turning the body as in a forehand	(1) Record the number of valid strokes by the participant, with a combined total of valid forehand and backhand strokes ≥ 6 (2) Record the number of valid serves by the participant within the specified time, with a combined total of valid hits in service box 1 and service box 2 being ≥ 8 shots	Standard tennis court
Underhand serve	The participant, positioned according to the singles serve stance as per tennis competition regulations, utilizes an underhand serve technique. The serving sequence includes 6 serves in service box 1 and 6 serves in service box 2, totaling 12 serves	1. A serve landing in the valid area is considered a valid shot 2. If the ball grazes the net, it is deemed a let and a re-serve is required 3. The test is terminated if it exceeds 2 min. Only valid shots completed within 2 min are recorded		

(1) Aerial volleys are considered invalid shots

(2) A volley landing within the singles court area is considered a valid shot

(3) Standing behind the service line, at the midpoint and assumed extension of the singles sideline. If a "foot fault" occurs, the shot is not counted

(4) Volleying must be done in mid-air, and both overhand and underhand serves are permissible. Hitting the ball again after it has landed is considered a serving error

(5) Failure to serve the ball into the specified area or serving into the wrong area is considered a serving error and not counted

teachers being informed of their group assignments only after the study concludes.

Implementation {16c}

To prevent contamination of the intervention, each of the five groups (four intervention groups and one control group) will undergo distinct sport-specific training (basketball, football, tennis, or martial arts). Participants will be instructed not to participate in other sports outside of the designated intervention during the trial period. The study team will regularly monitor adherence to this instruction. Any participant found engaging in additional sports will be excluded from the analysis to avoid confounding factors. This ensures that the effects observed are due to the specific intervention assigned.

Assignment of interventions: blinding

Who will be blinded {17a}

Participants, teachers in class, and outcome assessors will be blinded.

Procedure for unblinding if needed {17b}

Personnel who develop research plans will not be blinded. Throughout the entire research process, students participating in the intervention and teachers implementing the intervention will always be blinded.

Data collection and management

Plans for assessment and collection of outcomes {18a}

Comprehensive data collection and recording will be performed for both experimental and control groups. This included assessments of physical fitness, specialized sports skills, levels of physical activity, and fMRI measurements. Three tests (T1, T2, and T3) were administered during the baseline survey before the start of the intervention (Fig. 1). At the beginning of the school year, an informed consent form will be sent to the student's parents, who will be asked to sign the informed consent form. In high school, students will also receive written and oral information about the study. The tests will be administered by members of the research group who have no competing interests, and these testers will not have access to detailed information about the intervention group assignments. Before the tests, two training sessions will be conducted to ensure the quality of the assessments, with training led by professionals in the field. In addition, the personnel responsible for conducting the specialized sports skills tests must complete the training provided by the assessors of the "Standard of Competency in Youth Sports" to become qualified assessors.

Plans to promote participant retention and complete follow-up {18b}

The researcher will intermittently visit the school to carry out observations and research to observe the students while in class. This will allow for the identification and resolution of any issues that may arise among students during the intervention process.

Data management {19}

All research data entry will be done by two individuals, followed by an internal consistency check. The consent forms will be stored separately from the participant data, and each participant will be assigned a unique identification code. Once the data entry is complete, the data will be promptly deleted from the recording devices, and pseudonyms will be used in all reports instead of participants' names. Junior researchers and statisticians can only access the data after obtaining approval from the research group. The data will be retained for up to 5 years before being safely destroyed. A data security officer will oversee all phases of this study, overseeing data collection and analysis. This specialist will manage data and process data access requests without access to detailed study information. Test data will be managed following the data management plan developed and approved by the project team. In addition, data will be disseminated through two means: publication of academic papers and uploading them to the experiment registration website.

Confidentiality {27}

The collected data sheets and electronic data files will contain no personal information and each participant will be given a unique study code.

Plans for collection, laboratory evaluation and storage of biological specimens for genetic or molecular analysis in this trial/future use {33}

Data collection in this study did not involve biological specimens from participants.

Statistical methods

Statistical methods for primary and secondary outcomes {20a}

The questionnaire data in the study tracking the impact of sports skills on students' physical and mental fitness will be analyzed using SPSS 18.0, AMOS 18.0, and EXCEL. The primary statistical methods will be used in the analysis include descriptive statistics to summarize and describe the characteristics of the collected data, including means, standard deviations, and frequencies. *t*-Test for grouped data to compare means

between groups, such as specialized and non-specialized students, sports skills achievement levels and students' levels of physical activity in the classroom. Chi-square test to analyze categorical data and assess variable independence. Regression analysis will be used to explore relationships and associations between variables, such as the impact of sports skills on physical fitness and brain development. Structural equation modeling (SEM) will be conducted using AMOS 18.0 to investigate complex relationships and influence pathways, particularly the impact of sports skills learning on students' physical fitness.

A mixed-effects model for repeated measures will be used to estimate differences in physical fitness and brain structure over time (0, 6, and 12 months). This approach accounts for within-subject correlations and allows for the inclusion of missing data. Fixed effects will include group (intervention vs. control), time (0, 6, 12 months), and their interaction, while random effects will account for individual variability. Results will be reported with corresponding 95% confidence intervals (CIs). To handle the issue of multiple primary outcomes (physical fitness, specialized sports skills, and brain development) and reduce the risk of type I error: Bonferroni correction will be applied to adjust the significance threshold for multiple comparisons. Alternatively, false discovery rate (FDR) will be controlled for analyses involving correlated outcomes. Spearman correlation coefficients will be calculated to explore associations between sports skills scores and changes in physical fitness or brain function.

The neuroimaging data will be processed using Matlab R2013b and the DPARSFA (Data Processing Assistant for Resting-State fMRI Advanced Edition) software. The preprocessing steps include (i) conversion of raw DICOM data to NIFTI format; (ii) discarding the initial 10 time points, resulting in 230 stable time points; (iii) time layer correction; (iv) head movement correction, eliminating subjects with head movement parameters exceeding 2.0 mm in translation or 2° in rotation, resulting in 18 subjects; (v) regression covariates, including brain white matter signal, cerebrospinal fluid signal, and 24 head movement parameters; (vi) spatial normalization using DARTEL to convert functional images to Montreal Neurological Institute (MNI) standard space; and (vii) detrending and filtering (0.01–0.1 Hz). For local consistency analysis, the Kendall coefficient of concordance (KCC) will be used to calculate ReHo (regional homogeneity) values, assessing the similarity of the time series of each voxel with its neighboring voxels (26 neighboring voxels). Whole-brain ReHo images will then be spatially smoothed using a 6 mm × 6 mm × 6 mm Gaussian kernel to improve the signal-to-noise ratio.

The following statistical analyses will be performed on the neuroimaging data: ReHo maps at each time point (0 and 12 months) will be analyzed using one-sample *t*-tests, corrected for multiple comparisons using AlphaSim correction at $P<0.05$. Paired *t*-tests will be conducted to compare intragroup differences in ReHo values before and after the intervention (0 vs. 12 months) for both intervention and control groups. AlphaSim correction ($P<0.05$) will be applied to control for multiple comparisons. Spearman correlation coefficients will be calculated between ReHo values and sports skills scores to investigate the relationship between brain function and specialized sports skills. Multiple regression analysis will be conducted to explore the predictive value of ReHo values for changes in sports skills scores, with age, sex, height, and body mass included as covariates. Results will be corrected for multiple comparisons using AlphaSim at $P<0.05$. The results of the neuroimaging analysis will be visualized using xjview software.

Interim analyses {21b}

This study is scheduled for an interim analysis 6 months after the intervention, and the investigators will consider and decide to terminate the intervention if there is a serious adverse event related to the intervention that prevents it from proceeding. Thereafter, an interim analysis will be conducted based on the available data.

Methods for additional analyses (e.g., subgroup analyses) {20b}

Subgroup analysis of the primary and secondary outcomes will be performed according to gender.

Methods in analysis to handle protocol non-adherence and any statistical methods to handle missing data {20c}

Each participant's session attendance will be recorded to assess their adherence to the intervention, and participants will be considered to have not completed the intervention if they miss more than three consecutive sessions due to injury or other reasons. Data from participants who did not complete the intervention will not be included in the final data analysis.

Plans to give access to the full protocol, participant-level data and statistical code {31c}

The full protocol, participant data, and statistical codes are available from the relevant researchers upon reasonable request after the publication of the study results.

Oversight and monitoring

Composition of the coordinating center and trial steering committee {5d}

The coordinating center consisted of data collectors and researchers who are responsible for recruiting

participants, data collection, and periodic school-based interventions; the steering committee consisted of the principal investigator and assistant investigators, who are responsible for, among other things, the identification of the intervention protocol and the organization of the trial.

Composition of the data monitoring committee, its role and reporting structure {21a}

The data monitoring committee will be comprised of researchers with no competing interests in this study, and committee members will periodically evaluate the participants and make relevant recommendations.

Adverse event reporting and harms {22}

Establishment of a group chat using the public communication tool WeChat, where participants can report special situations directly to the investigators at any time in the communication tool, and the researchers will be immediately involved in the corresponding measures.

Frequency and plans for auditing trial conduct {23}

The researcher will regularly visit the intervention schools to keep abreast of the progress of the intervention and will report back to members of the trial steering committee and the coordinating center regularly to assess the progress of the intervention.

Plans for communicating important protocol amendments to relevant parties (e.g., trial participants, ethical committees) {25}

Any modifications to the protocol will be submitted by the principal investigator and approved by the Institutional Review Board of Shanghai University of Sport.

Dissemination plans {31a}

The results of the trial will be published in peer-reviewed journals and presented at scientific conferences.

Discussion

In China, the introduction of specialized sports skills teaching at the high school level offers a unique opportunity to carry out this study. This research not only verifies the effectiveness of specialized sports skills teaching in high schools but also provides crucial data to enhance the quality of specialized education. In addition, it serves as evidence to advocate for improved physical health and cognitive performance among adolescents. This study will conduct four distinct sports interventions with adolescents, with the overarching goal of examining the impact of sports skills acquisition on adolescents' physical fitness and brain structure. In addition, the study sought to investigate how different types of sports skills might influence the plasticity of adolescent brain structures. For teenagers, engaging in sports is an activity that integrates the use of their bodies, minds, brains, and intelligence. It serves as a purposeful means to encourage holistic development, encompassing physical, mental, and intellectual aspects. Adolescents are particularly critical to the development of sports skills, and the school environment provides an ideal setting and resources to facilitate this development. In this context, the study implemented sports skills interventions, making effective use of the school's facilities and equipment without the need for curriculum changes. As previously mentioned, the use of sports to enhance the physical fitness and cognitive abilities of children and adolescents offers significant benefits. A targeted sports intervention program not only contributes to young people's physical well-being but also enhances their mental health and overall cognitive functioning.

While existing evidence indicates the effectiveness of initiatives to enhance adolescent physical fitness and brain structure, it is important to acknowledge the relatively weak intensity of this evidence. This limitation stems from the preponderance of cross-sectional studies in the literature [27, 53, 54] and the scarcity of relevant research, especially in developing countries, with a notable gap in studies conducted in China. In the Chinese context, most research has focused on interventions related to children's physical activities, while there remains a significant lack of comprehensive, long-term follow-up studies focused on school-based sports skills interventions targeting improvements in physical fitness and brain structure among adolescents. Therefore, it becomes imperative to establish effective measures for sports skills interventions during this critical phase of adolescent physical and cognitive development. These interventions have the potential to significantly enhance the physical well-being and cognitive abilities of Chinese adolescents. Moreover, this long-term follow-up cohort study, rooted in sports skills, not only addresses these research gaps, but also lays the groundwork for future investigations into adolescent motor abilities, long-term health outcomes, and the intricate influence of brain development. Consequently, it not only contributes to the existing body of knowledge but also provides a platform for further exploration of adolescent development and overall well-being.

Trial status

This protocol is version 2, date: October 5, 2023. The study was approved by the Institutional Review Board (IRB) of the Shanghai University of Sport (102772022RT031) and registered by the China Clinical Trial Registry (ChiCTR2300070942). At the time of

manuscript submission, the research team had begun recruiting study participants; recruitment began on September 15, 2023, and is scheduled to be completed by March 10, 2024.

Abbreviations

fMRI	Functional magnetic resonance imaging
CRF	Cardiorespiratory fitness
20 m MSR	20-M multistage shuttle run
BMI	Body mass index
RS fMRI	Resting-state functional magnetic resonance imaging
IPAQ-SF	International Physical Activity Questionnaire Short Form
ICC	Intraclass correlation coefficient
SEM	Structural equation modeling
CI	Confidence interval
KCC	Kendall coefficient of concordance
MNI	Montreal Neurological Institute

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s13063-025-08788-9.

Supplementary Material 1.

Acknowledgements
The authors are particularly grateful to the teacher-researchers who agreed to participate in recruiting into Shanghai's high schools.

Authors' contributions {31b}
YK contributes to the research design and writing. MH and XL are responsible for collecting test methods. YP revised the manuscript. LL, YM, and YL confirm the feasibility of motor skills interventions. XK and YL supervised the drafting of the manuscript and reviewed it for important intellectual content. All authors listed have made a substantial, direct, and intellectual contribution to the work.

Funding {4}
This study is supported by grants from the Program for Overseas High-level Talents at Shanghai Institutions of Higher Learning (TP2022102) and the Research and Innovation Grant for Graduate Students (Shanghai University of Sport Project No. YJSCX-2023–012) and also supported by the Key Laboratory of Exercise and Health Sciences of the Ministry of Education, Shanghai University of Sport.

Data availability {29}
Data will be made available on reasonable request to the corresponding author.

Declarations

Ethics approval and consent to participate {24}
This study was approved by the Institutional Review Board (IRB) of the Shanghai University of Sport (SUS) (102772022RT031). Written informed consent will be obtained from all participants. The investigators will ensure that this trial is conducted by relevant Chinese clinical trial research norms and regulations.

Consent for publication {32}
All authors grant consent for publication.

Competing interests {28}
The authors declare that they have no competing interests.

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Received: 26 December 2023 Accepted: 4 March 2025
Published online: 24 March 2025

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