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Article

New applications of sports biomechanics in human health and athletic performance

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Abstract: The article explores the new applications of sports biomechanics in human health and athletic performance. Firstly, it introduces the fundamental principles of sports biomechanics, including its definition and mechanical principles, providing a theoretical foundation for subsequent research. In terms of health, sports biomechanics is applied to the prevention and assessment of sports injuries, enabling athletes and the public to gain a more comprehensive understanding of the potential risks in sports and to take effective measures to avoid injuries. Additionally, in rehabilitation therapy, sports biomechanics offers patients scientific training programs to enhance recovery outcomes. Furthermore, for adolescents with idiopathic scoliosis, sports interventions based on biomechanics have significantly improved athletic ability and quality of life. In the field of sports performance, sports biomechanics assists athletes in enhancing their competitive state and sustained performance by analyzing sports techniques and optimizing training methods. The article concludes by summarizing the importance and application prospects of sports biomechanics, demonstrating its potential in improving health levels and sports performance. By exploring the multiple functions of sports biomechanics, this paper provides new perspectives for improving sports training and health management, and advocates for the further application of this scientific tool in sports medicine and the fitness industry.

Keywords: sports biomechanics; human health; sports performance; new applications

1. Introduction

With the increasing societal focus on health and athletic performance, sports biomechanics, as an interdisciplinary field, is increasingly demonstrating its application value in these two areas. Sports biomechanics integrates biology, engineering, and sports science, and by studying the mechanical characteristics of the human body during movement, it aids in understanding movement patterns and their impact on health. Over the past few decades, sports biomechanics has played a significant role not only in athlete training and enhancing competitive performance but also in promoting public health, preventing sports injuries, and demonstrating strong potential in rehabilitation therapy. The fundamental principles of sports biomechanics provide us with tools to quantify and analyze human movement, effectively identifying potential risk factors during physical activity. For instance, by analyzing the distribution of forces and strains in joints and muscles during movement, we can gain insights into the causes of sports injuries, thereby formulating targeted prevention and intervention measures. In the field of rehabilitation, the application of sports biomechanics enables clinicians to design scientifically-based rehabilitation programs for patients, assisting them in recovering normal function and mobility more swiftly. Furthermore, concerning the prevalent health issue of adolescent idiopathic scoliosis, sports biomechanics also offers new solutions. Based on the growth and development characteristics of adolescents, research in sports biomechanics can help formulate practical sports intervention plans, thereby improving their physical condition and quality of life. In terms of athletic performance, sports biomechanics plays an equally important role. By optimizing sports techniques and training programs, researchers can assist athletes in enhancing performance and extending their athletic careers. Whether in athletics, ball sports, or other competitive events, sports biomechanics can analyze and adjust movement postures to achieve the goals of improving efficiency and reducing energy consumption [1].

Overall, sports biomechanics demonstrates infinite potential and value in maintaining and improving human health and enhancing athletic performance. This article will discuss the fundamental principles of sports biomechanics and explore its new applications in human health and athletic performance, providing new perspectives and ideas for advancing this discipline. We will gradually examine its specific applications in areas such as sports injury prevention and assessment, rehabilitation treatment, youth health intervention, and enhancing athletic performance, with the hope of providing beneficial references for research and practice in related fields.

2. The basic principles of sports biomechanics

2.1. Introduction to biomechanics of sports

The field of work for sports scientists is known as sports biomechanics, a discipline that focuses on studying the effects of various forces on human movement, covering multiple aspects such as gravity and air resistance, while also exploring how the human body exerts these forces externally during movement. The core value of sports biomechanics stems from the understanding of the fundamental laws between force and motion, particularly in practical applications within the fields of sports and training. The research content of sports biomechanics is quite extensive, including linear and angular kinematic analysis, which primarily involves the assessment of physical quantities such as position, displacement, velocity, and acceleration. Additionally, linear and angular dynamics, force analysis, exploration of motion laws, center of mass positioning, torque, and moment of inertia are all core elements of this field. Taking the starting motion of a sprinter as an example, the hip joint's extension process on the starting block perfectly illustrates the core parameters of linear kinematics—when the athlete's torso recovers from a 45° forward lean to an upright position, the center of mass of the body produces a horizontal displacement of 1.2 m within 0.3 s, with instantaneous acceleration reaching 9.8 m/s^2 (close to gravitational acceleration). During this process, the frictional force at the contact surface between the running shoes and the starting block (up to 2.5 times the body weight) directly affects acceleration efficiency, revealing the quantitative relationship between force and motion state. Angular kinematic analysis also has typical application value in gymnastic flips. When elite athletes complete a tucked backflip, they reduce the moment of inertia by 60% through hip flexion and knee contraction, subsequently increasing the angular velocity to 12 rad/s, ensuring a 1080° rotation is completed within 0.8 s of airtime. In the case of the giant swing on the horizontal bar, athletes optimize the rotation radius by precisely controlling the shoulder joint angle (maintaining a range of 170°–180°) to maximize rotational kinetic energy, a process that involves the dynamic balance of angular acceleration and torque distribution. The subsequent sections will discuss these standard biomechanical concepts in detail to enhance insights into the movement process.

When discussing sports biomechanics, gravity and air resistance are two crucial factors. Clearly, the role of these forces is the same in both athletic and non-athletic activities. For instance, a high jumper must overcome gravity to clear a higher bar, which is entirely consistent with the gravitational situations we face in our daily lives, such as climbing stairs or during an airplane takeoff. Similarly, whether it is a car traveling on a highway or a bicycle riding on the street, the air resistance that needs to be overcome is essentially no different. These examples clearly demonstrate that the principles of mechanics in everyday life are equally applicable to the analysis and practice of sports. Sports biomechanics is not limited to theoretical research; many practical applications have also been widely adopted. For example, in professional sports training, coaches utilize the principles of biomechanics to optimize athletes' techniques, thereby enhancing performance. By analyzing athletes' movements, coaches can identify areas for improvement, such as the efficiency of force usage during throwing, running, or jumping. Such analyses often incorporate high-tech equipment, such as motion capture systems and force platforms, to obtain precise data, which in turn helps in formulating more scientific training plans for athletes.

In biomechanical research, **Figure 1** presents a classic example that demonstrates the forces acting on the biceps when supporting a sphere from an anatomical perspective [3]. This example also illustrates how to integrate mechanical principles with anatomy to gain a deeper understanding of the role of forces in various movements. In this way, we can gain insights into the functioning of muscles during different phases of movement while predicting the physical stress and risks athletes may encounter under specific conditions. Furthermore, this comprehensive research not only aids athletes in achieving technical breakthroughs but also plays a role in preventing sports injuries. By understanding which forces may lead to injuries in specific movements, coaches and athletes can strategically adjust training to reduce the risk of injury. The value of biomechanics in this regard lies in its role as an important tool for enhancing athletic performance and as a crucial basis for ensuring athlete health.

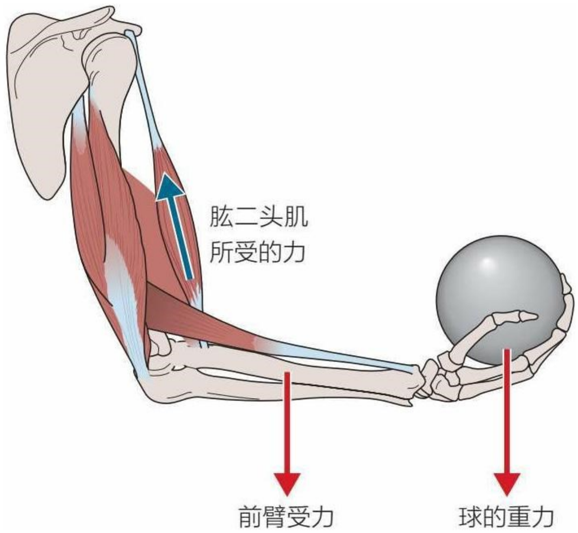

Figure 1. The mechanical force that causes the biceps to support the ball.

2.2. Principles of mechanics

In sports activities, the principles of mechanics are the fundamental physical laws that influence the actions of athletes. For instance, if coaches and athletes have a clear understanding of gravity, they can find ways to mitigate its effects or, in certain cases, utilize it. The following are some relevant examples.

If platform divers understand the vertical force of gravity, they can have a more accurate grasp of the trajectory of their descent, thereby achieving the optimal entry angle when diving. Wrestlers, if they recognize the supportive effect of gravity, can utilize it to force their opponents off balance. However, if a wrestler fails to maintain their own stability, it may inadvertently benefit their opponent. Ski jumpers should also be aware that by bending their legs and leaning their upper body forward, they can streamline their bodies, reducing air resistance during their downward sprint, thus gaining greater acceleration to prepare sufficient speed before takeoff, which is crucial for completing a parabolic motion. This will be further explored later.

Once the ski jumper takes off, they begin to utilize air resistance to counteract gravity. At this moment, they extend their legs, lean forward, and compress the air downward, generating an upward thrust. The combination of gravity and air resistance assists the ski jumper in achieving a flight distance exceeding 130 m [4]. In addition to gravity and air resistance, there are various other forces at play during movement, each affecting the athlete in its own way. In sports that require physical contact with opponents, athletes must also consider the forces exerted by their counterparts. A coach's profound understanding of these forces will aid in more effectively analyzing an athlete's skills, thereby enhancing their performance. Athletes who master this knowledge can more accurately determine the optimal points of force application, showcasing the best movement techniques. Even spectators or sports enthusiasts can elevate their knowledge level by learning the principles of mechanics, enabling them to better identify the characteristics of optimal athletic performance.

2.3. Application of biomechanical principles in rehabilitation equipment

The design of sports rehabilitation therapy equipment is highly dependent on an in-depth understanding of the biomechanical systems of the human body. This kind of device has become an important technical support for modern rehabilitation medicine by accurately simulating the normal movement mode of the human body and constructing a mechanical environment that conforms to the laws of tissue repair. Its core technology lies in establishing a dynamic balance system between motion control, mechanical feedback and neural adaptation.

2.3.1. Principle of motion chain simulation

The advanced isokinetic strength training equipment utilizing closed-loop torque control technology achieves dynamic resistance adjustment within the range of 0–500 Nm through a magnetorheological damping system. The biomechanical core of the system maintains the adjustment of resistance load based on real-time electromyographic signals while keeping the joint angular velocity constant. This design simulates the relationship between the tibial displacement trajectory and the activation timing of the quadriceps muscle captured by three-dimensional mechanical sensors during flexion and extension movements in knee rehabilitation training, thereby establishing a personalized resistance curve to ensure that the training load consistently matches the patient's muscle fiber recruitment capacity, thus realizing the interactive relationship of "joint torque-muscle synergy" in the human movement chain. The gait analysis training system combines three-dimensional motion capture with ground reaction force monitoring technology to conduct comprehensive training. Its pressure distribution sensor array reconstructs the contraction timing of various muscle groups during the walking cycle using biomechanical modeling software, capturing plantar dynamics parameters at a sampling rate of 2000 Hz. This device is particularly suitable for the rehabilitation of motor functions in stroke patients, with its design based on the theory of "energy transfer in the lower limb movement chain"—reconstructing gait characteristics that conform to biomechanical efficiency and correcting abnormal patterns of hip-knee-ankle movement coupling in patients through a real-time feedback system.

2.3.2. Dynamic stability control technology

The neuromuscular control training device integrates a six-degree-of-freedom motion platform with a gaze tracking system to work in synergy. Such devices create a controllable unstable support surface that accurately replicates the ankle strategy, hip strategy, and stepping strategy involved in dynamic balance processes. The core technology lies in establishing a biomechanical coupling model of vestibular, proprioceptive, and visual inputs. Taking the balance function rehabilitation of patients with brain injuries as an example, the device can dynamically adjust the platform's tilt angle (0–15° adjustable) based on the patient's center of pressure (COP) movement trajectory, while simultaneously providing visual-vestibular matching training through a virtual reality system. This multimodal stimulation significantly enhances the efficiency of neuromuscular adaptation. The suspended vibration therapy system parameterizes the combination of vibration frequency (20–50 Hz) and suspension angle (0–60°), designed based on the biomechanical mechanism of "muscle vibration-induced neural inhibition." When the device applies axial vibration, the discharge frequency of the spindle afferent fibers changes, prompting the central nervous system to reorganize motor control strategies. Clinical studies indicate that for patients with chronic low back pain, a vertical vibration of 30 Hz combined with a suspension angle of 45° can increase the activation efficiency of the multifidus muscle by 42%, while simultaneously reducing compensatory activity of the erector spinae.

2.3.3. Biomechanical optimization of human-machine interaction

The intelligent prosthetic system integrates a fusion algorithm of electromyographic signal acquisition (with a sampling rate of 1000 Hz) and an inertial measurement unit (IMU). Its knee joint mechanism employs a bionic four-bar linkage design, dynamically optimizing the stiffness coefficient of the energy-storing spring (5–20 N·m/rad) during the gait cycle to achieve biomechanical matching of energy storage in the support phase and energy release in the swing phase. This phase-dependent impedance control technology can reduce the gait asymmetry index of amputees to below 8%. The force feedback rehabilitation robot achieves a force control accuracy of 0.1 N through a series elastic actuator (SEA). Its tactile interface utilizes a piezoresistive array sensor (with a spatial resolution of 2 mm), capable of accurately capturing the patient's active movement intentions. In the upper limb rehabilitation of stroke patients, the device automatically adjusts the assistive torque (0–30 Nm) and constructs a virtual impedance environment based on musculoskeletal models according to the Fugl-Meyer score. This "adaptive assistance" strategy significantly enhances the efficiency of motor learning. The design of modern rehabilitation equipment has evolved from simple mechanical simulation to the intelligent integration of multimodal biomechanical systems. The new generation of devices can create individualized training environments in biomechanics through the integration of kinematic analysis, dynamic modeling, and neurophysiological feedback technology. This technological evolution not only improves the effectiveness of rehabilitation treatment but also provides new research dimensions to understand the fundamental laws of human movement control. Future development trends will focus on the deep integration of wearable biomechanical sensing systems and cloud-based intelligent analysis platforms for remote rehabilitation training.

3. New applications of sports biomechanics in human health

3.1. Prevention and assessment of sports injuries

Sports injuries primarily involve damage to the musculoskeletal system and frequently occur among individuals engaged in physical training and exercise, particularly those who are new to these activities. The main causes of these injuries include improper technical movements, non-standard use of venues and equipment, and excessively high-intensity training. Improper technical movements refer to actions performed during exercise that do not align with an individual's anatomical structure and physiological function requirements, nor do they adhere to the relevant principles of sports biomechanics. Some of these technical movements are basic requirements of competitive sports, while the vast majority stem from a lack of understanding of such knowledge and concepts. From the perspectives of human anatomy, physiology, and sports biomechanics, incorrect sports techniques not only hinder the improvement of athletes' competitive levels and abilities but also become common factors that lead to sports injuries.

The subjects of this study are athletes from sports universities, national training teams, and various provinces, cities, and universities, totaling 675 individuals, comprising 423 males and 252 females. Their age distribution is as follows: 90 individuals aged 14–17, 430 individuals aged 18–21, and 155 individuals aged 21–28. They are classified according to the causes of injury, nature of injury, and injury location. The research data is sourced from the following institutions: 1) Sports Science Research Institute and Department of Biological Sciences of Beijing Sport University 2) Sports Medicine Research Institute of Beijing Medical University 3) Training Bureau of the General Administration of Sport of China [5].

According to **Table 1**, the main factors contributing to sports injuries include improper technical movements, insufficient warm-up activities, and non-compliance of venues and equipment standards. Among these, the injury incidence caused by improper technical movements is the highest. Such issues are very common across various sports. For instance, aerial errors in gymnastics may lead to injuries in areas such as the knee joint and spine; rapid rotations in athletics may injure the knee joint; shoulder errors during javelin throwing may cause elbow injuries; and backhand strokes in tennis, badminton, and table tennis may trigger arthritis. In the two high-frequency injury scenarios of backhand strokes in badminton and jumping and landing in basketball, there are significant differences in the mechanical mechanisms of technical movement deviations. When badminton players perform backhand strokes, insufficient external rotation of the shoulder joint (<40°) and excessive extension of the elbow joint (>15°) lead to a high incidence of lateral epicondylitis, with the core issue being that the rotational kinetic energy of the trunk (approximately 65%) is not transmitted progressively through the "hip-shoulder-elbow-wrist" sequence, resulting in a sudden increase in energy at the elbow joint (local load exceeding baseline value by 200%). Simultaneously, excessive activation of the pronator teres and delayed activation of the infraspinatus exacerbate the loss of scapular stability. In contrast, during jumping and landing in basketball, the inward angle of the knee joint exceeding the safety threshold increases the risk of anterior cruciate ligament (ACL) injury by 3.2 times, primarily due to insufficient activation of the hip abductor muscles leading to compensatory internal rotation of the femur, compounded by a vertical ground reaction force (vGRF) peak reaching 4.2 times body weight and a deviation of the force line from the rotational center of the knee joint (displacement >2 cm).

For the issue of backhand strokes in badminton, real-time monitoring of trunk rotation angular velocity (target ≥300°/s) can be achieved through inertial sensors, combined with resistance rotational medicine ball training (resistance band 10–15 kg) to enhance the scapula-thoracic linkage efficiency, thereby reducing energy transfer loss; regarding landing injuries in basketball, an augmented reality (AR) system is employed to simulate scenarios, training the synchronous pattern of ankle dorsiflexion and hip abduction (inversion angle reduced by 42%), and developing gradient compression knee pads (pressure gradient 15–25 mmHg) to guide patellar trajectory (lateral shift reduced by 0.6 cm). Both cases confirm that through biomechanical parametric modeling and real-time feedback technology, the transformation of movement patterns from “compensatory adaptation” to “efficient transfer” can be achieved, effectively enhancing athletic performance while controlling injury risk within the biological tolerance threshold.

Table 1. Classification statistics of damage causes ($N = 120$).

Reason	Number of examples	Ratio (%)
The situation of non-standard technical actions and abnormal performances.	55	45
High-intensity high-risk training	10	8
Improper use or unexpected changes of venues and equipment.	20	17
The arrangement of the warm-up activities is unreasonable.	28	24
Other factors	7	6

Table 2 shows that soft tissue injuries account for the highest proportion, reaching 39%, with a total of 46 cases. This indicates that the protection of soft tissues is particularly important during sports activities. Following closely are joint capsule and ligament injuries, which rank second at a rate of 30% (37 cases), suggesting that special attention should be paid to the protection and strengthening of these structures during training. Bone injuries and visceral injuries each account for 12% (14 cases respectively), indicating that bones and internal organs also face certain risks during sports. Therefore, athletes need to be fully aware of the strength of their bones and the protection of their internal organs when engaging in sports. Lastly, other types of injuries account for 7% (9 cases). By analyzing this data, a deeper understanding of the types of sports injuries can be gained, leading to the development of more effective prevention and assessment strategies to reduce the incidence of sports injuries and ensure the health and safety of athletes.

Table 2. Classification statistics of damage nature ($N = 120$).

Organizational structure	Number of examples	Ratio (%)
Soft tissue damage	46	39
The joint capsule and ligaments are damaged.	37	30
Bone damage	14	12
Internal organs damaged	14	12
other	9	7

Table 3 shows the distribution of sports injuries in different body parts. A total of 120 cases of sports injuries occurred in the head, neck, shoulder, arm, waist, abdomen, chest, back, elbow, forearm, wrist, palm, thigh, calf, foot, and coccyx. Among these, the highest number of injuries occurred in the waist and abdomen, accounting for 25% of the total cases, followed by the shoulder and arm, which accounted for 16%. This set of data helps individuals understand the common sites

of sports injuries, thereby enabling targeted prevention and assessment measures to reduce the incidence of sports injuries and promote safety in sports.

Table 3. Classification statistics of damage occurrence locations (*N* = 120).

Site of occurrence	Number of examples	Ratio (%)
head	6	5
neck	11	9
Shoulders and spine arms	19	16
Waist and abdomen	30	25
Chest and back	6	5
Elbow forearm	9	7
Wrist Palm	5	4
Pulp thighs	6	5
Medullary calf	8	7
Restlessness	8	7
Glutecoccygeal vertebrae	12	1

In the javelin throw, many athletes encounter pain on the inner side of the right foot during the full approach and throw. Through technical diagnosis, we found that most athletes form an angle close to vertical between the right foot and the throwing direction when transitioning from the throwing step to the cross step, which significantly affects their training and competition performance [6]. From a biomechanical perspective, during the javelin throwing process, the athlete's speed and center of gravity gradually decrease, leading to a more pronounced extension of the lower limbs and an overreach of the upper limbs. Particularly during the cross step, the athlete's speed is at its peak, and the center of gravity drops significantly to the right, with the stride being the longest, which causes the right foot to bear the greatest portion of the ground reaction force. However, the human body's ability to withstand external pressure is closely related to posture. The alignment of bones, joints, and muscles should be consistent with the direction of movement, and muscles need to contract synchronously while maintaining a small angle. Yet, in actual movement, technical actions often contradict these principles. In the cross step, the way the right foot lands deviates from the longitudinal axis, resulting in an incomplete extension of the lower limbs, thereby reducing the supporting reaction force and movement speed. Therefore, it is crucial to reduce injuries and improve athletic performance in javelin throwing. We need to achieve a balance between effectively executing competitive actions and maintaining optimal mechanical posture to enhance the athlete's competitiveness.

3.2. Rehabilitation therapy and training

In recent years, the rise of the self-rehabilitation concept has ushered in a new wave of enthusiasm in the field of rehabilitation. Traditional rehabilitation methods primarily rely on the direct guidance of professional rehabilitation therapists and medical teams for patients. Although this model is filled with human emotions, it also carries significant burdens and resource constraints. Traditional rehabilitation medicine has long depended on the experiential judgment and manual operations of therapists, and this "manual-experience" model has gradually revealed systemic flaws in clinical practice. The subjective assessments of therapists exhibit considerable individual differences, and a single training session can only cover fragmented records of a patient's motor functions. More critically, traditional methods struggle to quantify the subtle changes in neuromuscular function— for instance, the progressive improvement from Brunnstrom stage III to IV in the upper limbs of stroke patients is often roughly categorized as "the emergence of partial separation movements," a qualitative description that fails to guide precise dose-effect relationship regulation. Consequently, the scientific community has begun to explore new rehabilitation assessment methods in an effort to break the limitations of experience dependence. After nearly thirty years of research and practice, we have acquired important knowledge regarding neurological rehabilitation [7]. Studies indicate that the human brain can appropriately adjust its structure and function upon receiving suitable stimuli, thereby facilitating the physical recovery of patients. Particularly in the early stages of rehabilitation, training with moderate intensity and reasonable duration yields remarkably significant effects. On the other hand, excessive rest may lead to muscle atrophy, negatively impacting rehabilitation outcomes. Therefore, timely training is crucial for patient recovery. Today, scientists have integrated knowledge from various fields, such as biology, mechanics, and computer technology, to develop a new generation of rehabilitation devices [8]. These devices effectively address the shortcomings of traditional methods, significantly enhance rehabilitation outcomes, alleviate the burden on rehabilitation therapists, and present patients with diverse training options through scientific evaluation methods [9,10].

The development of rehabilitation robots clearly demonstrates the logical context of technological iteration. The Handy1 robot, introduced in 1987, although only equipped with a single degree of freedom for grip assistance, holds significant importance as it was the first to incorporate servo control theory into rehabilitation training—achieving a torque control precision of 0.1 N·m through PID algorithms, which simulates the fine tactile feedback of a therapist's manual operation at the finger joints. The emergence of the MIT-MANUS system in 2005 marked a qualitative change in human-computer interaction technology, with its admittance control algorithm capable of recognizing 0.5% of the patient's active movement intention, facilitating a paradigm shift from "passive traction" to "adaptive assistance." Although China started relatively late in this field, in recent years, domestic universities and research institutions have actively engaged in the development of related equipment, which not only promotes the advancement of devices but also increases public attention to this field. Existing rehabilitation equipment can meet the specific training needs of different patients in various parts of the upper limbs, lower limbs, and the whole body. The asymmetric planetary gear mechanism developed by Hefei University of Technology showcases innovative breakthroughs in domestic equipment. This device accurately reproduces ankle dorsiflexion (12.3° ± 0.2°) and plantarflexion (40.1° ± 0.3°) movements in the sagittal plane [11], with trajectory errors reduced by 58% compared to the German LokomatPro. However, in terms of energy consumption efficiency, the advantages of domestic equipment are even more pronounced: the Hefei device consumes 0.8 kWh per training session, while the hydraulic drive system of LokomatPro requires 18 kWh/hour, resulting in a nearly 20-fold difference in daily usage costs in grassroots hospitals (80 yuan vs 1500 yuan, respectively). The German Motomed equipment has opened another technological path through modular design. Its switching between upper and lower limb training modes can be completed within 30 s [12], supporting a continuous transition from fully passive (0 rpm) to resistance training (50 Nm). Clinical data shows that for patients with spinal cord injuries, the passive cycling mode of Motomed can reduce the atrophy rate of the quadriceps from 2.1% per week to 0.7% per week, but the electromyography-triggered active mode is only suitable for patients classified as ASIA grade C and above (with a completion rate of less than 15% for grade B patients).

It is worth noting that the new devices do not simply replace traditional methods. During the acute phase of a stroke (<3 weeks), the key point control in traditional Bobath techniques still has an irreplaceable effect on neural inhibition; however, when patients enter the recovery phase (>6 weeks), the repetitive rhythmic movements provided by exoskeleton robots (1000 times/hour) significantly outperform the training efficiency of manual operations. This trend of technological integration is reflected in the latest generation of rehabilitation systems, such as Hocoma’s LokomatPro, which transforms the therapist’s manual guidance into robotic impedance control parameters, achieving human-machine collaborative therapy through adjustable assistive forces ranging from 0 to 100 N.

Despite the significant advancements in functionality and effectiveness of existing equipment, there are still challenges such as large device size and high costs, which limit their promotion and popularization in more community hospitals and homes. Therefore, continuing to drive innovation in rehabilitation technology and developing more compact, economical, and intelligent devices has become an important direction for future development. Through relentless research and innovation, we hope to provide better rehabilitation solutions to help more patients recover their health as soon as possible.

Figure 2. Lower limb rehabilitation device of Hefei university of technology.

(a) **(b)**

Figure 3. German motomed.

3.3. Sports intervention for adolescents with idiopathic scoliosis

The spinal health of adolescents is closely related to the coordination of exercise biomechanics. Idiopathic scoliosis is a phenomenon where the spine deviates from the centerline in a certain area, resulting in a C-shaped or S-shaped posture, as shown in **Figure 4**. This condition typically arises during puberty and may adversely affect skeletal health, leading to physiological deformities. By applying the principles of optimized exercise biomechanics and incorporating appropriate exercise programs, the structure and function of the spine can be improved, supporting the healthy development of the skeleton, thereby playing a positive role in the prevention and treatment of idiopathic scoliosis [13].

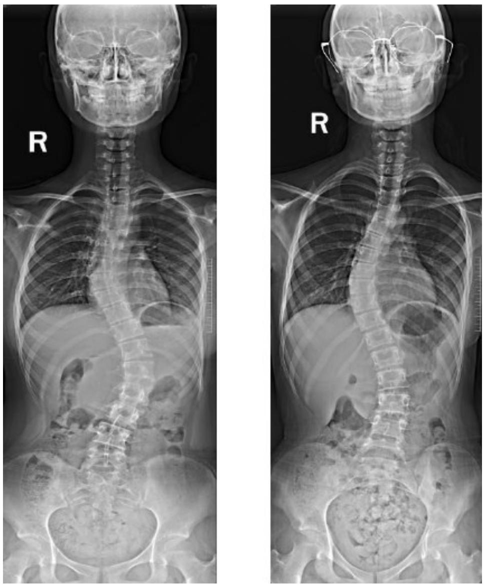

Figure 4. X-rays.

In the context of the high incidence of adolescent idiopathic scoliosis today, scientifically effective methods of physical exercise are particularly important for the prevention and correction of this condition. This is mainly because most adolescents do not exhibit obvious symptoms in the early stages, and the development of idiopathic scoliosis is rapid, often becoming quite severe by the time it is detected, making treatment more difficult and often less effective [14]. This situation not only has the potential to lead to disability but also increases the necessity for surgery. If preventive and corrective measures can be taken early, it is possible to effectively avoid surgery and reduce the risk of disability. Physical exercise is regarded as an effective means to help reduce the probability of idiopathic scoliosis while also promoting the recovery of those adolescents already affected to a more normal state, thereby preventing the negative impacts of this condition on physical and mental health [15]. Adolescents who lack exercise are often prone to health issues such as declining vision and weight gain, and may also increase the likelihood of developing idiopathic scoliosis. Parents need to pay attention to whether their children exhibit signs of uneven shoulder height, which may be an early signal of the disease. In addition to young people, adults who engage in prolonged office work or excessively use electronic devices can also harm their health. Regardless of posture, maintaining the same position for extended periods can be detrimental to the spine. Therefore, moderate physical activity is crucial for the prevention and alleviation of idiopathic scoliosis. Swimming is an excellent sport suitable for children with mild spinal curvature, as the buoyancy of water can effectively reduce the gravitational burden on the body and help relieve muscle tension. Furthermore, swimming can enhance cardiovascular function, improve chest flexibility, reduce muscle fatigue, and strengthen core muscle groups. To effectively prevent idiopathic scoliosis, adolescents should also actively participate in activities such as stretching, jumping, and strength training to promote healthy bone growth. During these activities, safety and moderation should always be prioritized to avoid exercise-related injuries.

Many experts and researchers unanimously believe that sports rehabilitation therapy is an extremely effective intervention method for adolescents with idiopathic scoliosis. A large number of empirical studies indicate that physical exercise has a positive effect on improving the physiological curvature of the spine in adolescents, not only effectively reducing the degree of spinal curvature but also enhancing the strength of related muscles [16]. However, there is also duality in the process of correcting adolescent idiopathic scoliosis through physical exercise. Key issues that urgently need to be addressed in current research include how to develop a scientifically sound rehabilitation training program, select appropriate types of exercise for patients, determine suitable exercise volume, and choose appropriate methods and ranges for strength training. Idiopathic scoliosis not only affects children's physical health but also severely impacts their mental health and growth. Although sports rehabilitation training is regarded as a novel and effective non-surgical method and has shown good results in psychological treatment, how to combine this exercise rehabilitation with psychological correction to achieve optimal therapeutic effects remains an important direction for future research. Therefore, regardless of the severity of the disease, children with idiopathic scoliosis should seek medical attention as early as possible to prevent further deterioration of their condition.

Based on this, we recognize that the prevention and treatment of idiopathic scoliosis through physical exercise is crucial. We need to emphasize how to guide adolescents through exercise training to reduce the risk of idiopathic scoliosis. At the same time, specific corrective training should be provided for those adolescents who have already developed scoliosis issues, to assist them in achieving comprehensive physical and mental health development.

4. New applications of biomechanics in sports performance

The secrets of movement lie in a multidimensional and complex network, reflected in the interactive relationship between the human body and the movement environment. By applying the principles of sports biomechanics, we can gradually deconstruct the various elements of movement actions to optimize performance and reduce the risk of injury. Research indicates that efficient movement skills hinge on perfect coordination of actions, which requires meticulous spatial and temporal planning of each independent action, allowing them to harmoniously combine to achieve specific movement goals. This analysis of movement patterns not only aids in understanding the complex interactions in sports but also provides a scientific basis for enhancing athletic levels and technological innovation [17].

When discussing the diverse applications of sports biomechanics, this article takes adolescent male volleyball players as an example to study the key techniques and their movement patterns in volleyball. The success of spiking and jump serving often relies on two core movement patterns: jumping and arm swinging, while receiving and serving are closely related to the athlete's mobility. Recent research has revealed the importance of sports biomechanics in tennis, particularly in key technical aspects such as hitting, serving, blocking, and receiving [18]. By analyzing the movement patterns of athletes, we identify that jumping, moving, and arm swinging are the core elements of these techniques. Therefore, it is particularly important for adolescent male volleyball players to clarify their characteristics and training points in these fundamental movements. This study focuses on two main directions: first, utilizing biomechanical testing methods to evaluate specific movement patterns; second, establishing concrete methods for assessing movement performance. We selected biomechanical test movements related to jumping and, in conjunction with international research data, expert advice, and practical experience, established two important testing indicators: jump height and repeated jump ability [19]. **Table 4** presents the preliminary testing indicators of the professional sports patterns of young male volleyball players, which will assist us in gaining a deeper understanding of athlete performance and provide a scientific basis for developing effective training programs. In the study of sports biomechanics, we will conduct a detailed analysis of athletes' movement patterns, covering various indicators such as muscle strength, flexibility, and coordination. This data will provide us with in-depth insights into athletes' performance across different movement patterns, thereby offering important references for revising and improving training plans. Through an in-depth exploration of sports biomechanics, we can gain a more comprehensive understanding of athlete performance and further enhance their competitiveness in competitions. At the same time, this will also assist coaches in formulating more targeted training plans for athletes, helping them improve their skills and physical fitness to achieve optimal competitive conditions.

Table 4. Preliminary testing indicators for specialized movement patterns of youth male volleyball athletes.

Level 1 Indicators Level 2 Indicators Level 3 Indicators	Level 1 Indicators Level 2 Indicators Level 3 Indicators	Level 1 Indicators Level 2 Indicators Level 3 Indicators
A1 Athletic organisms Mechanical testing action	B1 Jump Action Mode	C1 Two-step run-up and jump;
		C2 swings on the spot and jumps;
		C3 Jumps on the spot
		C4 Cross-waist squat jump;
		C5 cross-waist squat jump;
		C6 Squat and jump on the spot with swinging arms;
		C7 Squat and jump under the net;
		C8 Running and jumping;
		C9 Jump depth (30 cm);
	B2 jump height	C10 Left side by side to block the net and jump;
		C11 Right side by side to block the net and jump;
		C12 Left cross-step to block the net and jump;
		C13 Right cross-step to block the net and jump
A2 Movement performance Test Method:	B3 repetitive jumping performance	C14 15 s continuous jump;
		C15 30 s continuous jump;
		C16 60 s continuous jump;
		C17 60 s intermittent jump;
		C18 25 consecutive squat jumps;
		C19 6 sets of 6 consecutive jumps

Table 5 presents the results of the expert questionnaire survey. To assess the reliability of the expert questionnaire, this study employed Cronbach's alpha coefficient for analysis [20]. During the collection of the two rounds of questionnaires, the obtained Cronbach's alpha values were 0.934 and 0.775, respectively. This indicates that the questionnaire demonstrates good reliability in the field of sports biomechanics research, enhancing the credibility and validity of the data results. This assessment lays a solid foundation for subsequent research work.

Table 5. Results of the validity test of the expert questionnaire.

Effectiveness indicators	Very reasonable.	Relatively reasonable.	Rational	Unreaso-nable	Very unreasonable.
Content	66.70%	33.30%	0	0	0
Structure	33.30%	66.70%	0	0	0
Overall design	83.30%	16.70%	0	0	0

The research team conducted an in-depth analysis of the feedback from expert questionnaires, employing rigorous statistical methods to comprehensively evaluate various testing actions and their related indicators. After two rounds of investigation and multiple screenings, a scientific and effective evaluation system has been established, as shown in **Table 6**. The construction of this system provides important evidence for the application of sports biomechanics in athlete training and competition, particularly in enhancing athletic performance, where it has a significant guiding role. Through the assessment and analysis of specific movement patterns of athletes, researchers are able to gain a more comprehensive understanding of the technical characteristics and physical conditions of athletes, thereby providing data support for the development of personalized training programs and improving competitive performance.

Table 6. Test scheme of special movement mode of junior male volleyball players.

Primary Indicators	Secondary indicators	Tertiary indicators
Sports Biomechanics Testing Movements	Jump action mode	Two-step run-up jump;
		Vertical jump with net interception;
	Jump height	Arm swing squat jump from a standstill;
		Run-up jump;
Movement Performance Testing Methods	Repetitive jumping performance	15 s of continuous jumping

As shown in **Figure 5**, this study focuses on the specific movement patterns of adolescent male volleyball players, conducting an in-depth exploration through kinematic and electromyographic analysis. We performed a detailed kinematic analysis and electromyography monitoring of the jumping techniques of 15 outstanding young male volleyball players to comprehensively assess their athletic performance. Furthermore, we examined the kinematic factors and muscle activation patterns involved in these technical movements. Based on a thorough understanding of the requirements for specialized skills, we designed a training program aimed at enhancing the athletic functionality of adolescent male volleyball players, with a strong emphasis on relevant training concepts and principles.

In the action of running and jumping, the activation patterns of lower limb muscles show significant differences, as indicated in **Table 7** and **Figure 6**. During the cushioning phase, the study found that the activation level of the tibialis anterior is significantly higher than that in the push-off phase, suggesting that the tibialis anterior plays a crucial role during the cushioning phase. Conversely, in the push-off phase, the activation levels of the gastrocnemius muscles are higher, indicating that these muscles play an important role in propulsion during this phase. Furthermore, although the activation level of the quadriceps group increases during the push-off phase, this increase does not reach statistical significance. It is noteworthy that the activation level of the gluteus maximus is higher during the cushioning phase, which is related to its functional role in movement. Upon further analysis of the functional role of the gluteus maximus, it was found that there is a deficiency in the force output of the gluteus maximus during the push-off phase, providing a reference for further optimizing movement techniques. Through such analysis, a better understanding of muscle activation patterns in sports can be achieved, which is significant for optimizing training and enhancing competitive performance. This biomechanical approach not only helps improve athletes' performance but also has a positive impact on reducing sports injuries and enhancing safety in sports.

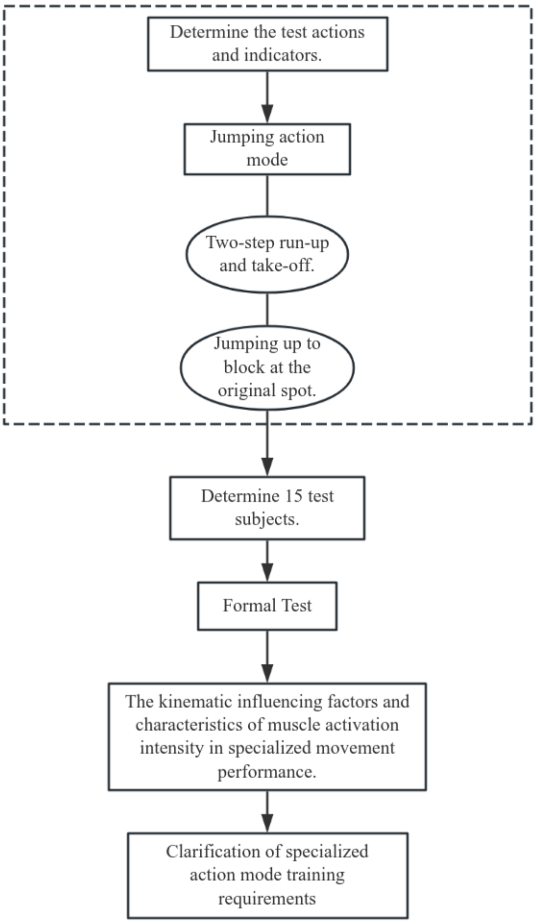

Figure 5. Research route.

Table 7. Activation levels (%) of lower limb muscle groups in the running and jumping movement patterns.

	Buffer phase		Extension phase	
Muscle Names	**Average**	**Standard deviation**	**Average**	**Standard deviation**
Gluteus Maximus	47.8	18.9	32.3	7.8
Biceps Femoris	35.2	8.7	35.7	9.4
Rectus Femoris	48.3	17.6	52.4	10.6
Vastus Lateralis	47.8	13.2	54.2	8.7
Vastus Medialis	42.7	13.8	47.6	8.4
Tibialis Anterior	46.3	9.7	25.2	8.5

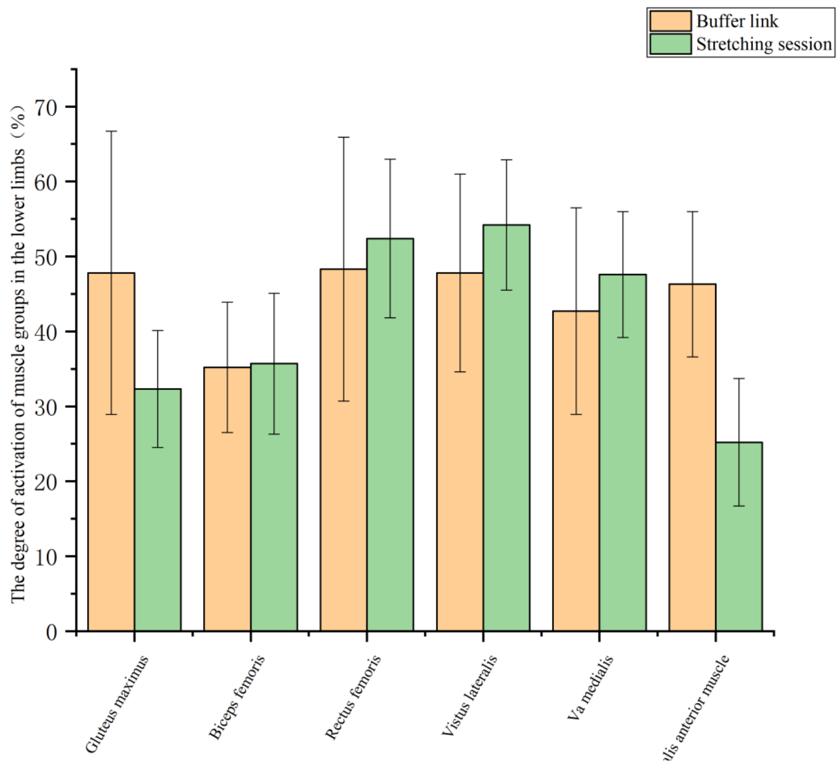

Figure 6. Degree of activation of lower limb muscle groups in the movement modes of running and jumping.

During the approach and take-off phases, the muscle activation patterns of the trunk and upper limbs are crucial, as shown in **Table 8** and **Figure 7**. By comparing the muscle activation during the buffering phase and the push-off phase, we found that the activation level of the erector spinae during the buffering phase was significantly higher than that during the push-off phase ($P < 0.01$). On the other hand, during the push-off phase, the activation levels of the anterior deltoid ($P < 0.05$), posterior deltoid ($P < 0.01$), triceps brachii ($P < 0.01$), and rectus abdominis ($P < 0.01$) all showed significant increases. These muscles play a key role in shoulder joint flexion and upper limb swinging. The analysis indicates that the activation of the erector spinae during the push-off phase is relatively low, thus emphasizing the importance of enhancing and training the activation of the erector spinae in sports training. Such research not only helps to improve training methods but also effectively enhances the overall performance of athletes.

Table 8. Activation intensity (%) of trunk and upper limb muscle groups in the running and jumping movement patterns.

	Buffer phase		**Extension phase**	
Muscle Names	**Average**	**Standard deviation**	**Average**	**Standard deviation**
Anterior Deltoid	31.2	16.8	42.6	15.9
Posterior Deltoid	17.5	12.9	36.4	9.4
Biceps Brachii	32.7	15.6	37.3	10.3
Triceps Brachii	16.3	8.7	32.4	10.5
Erector Spinae	46.8	14.5	33.6	9.7
Rectus Abdominis	8.9	9.5	23.7	8.1
Latissimus Dorsi	44.2	11.8	31.8	12.3

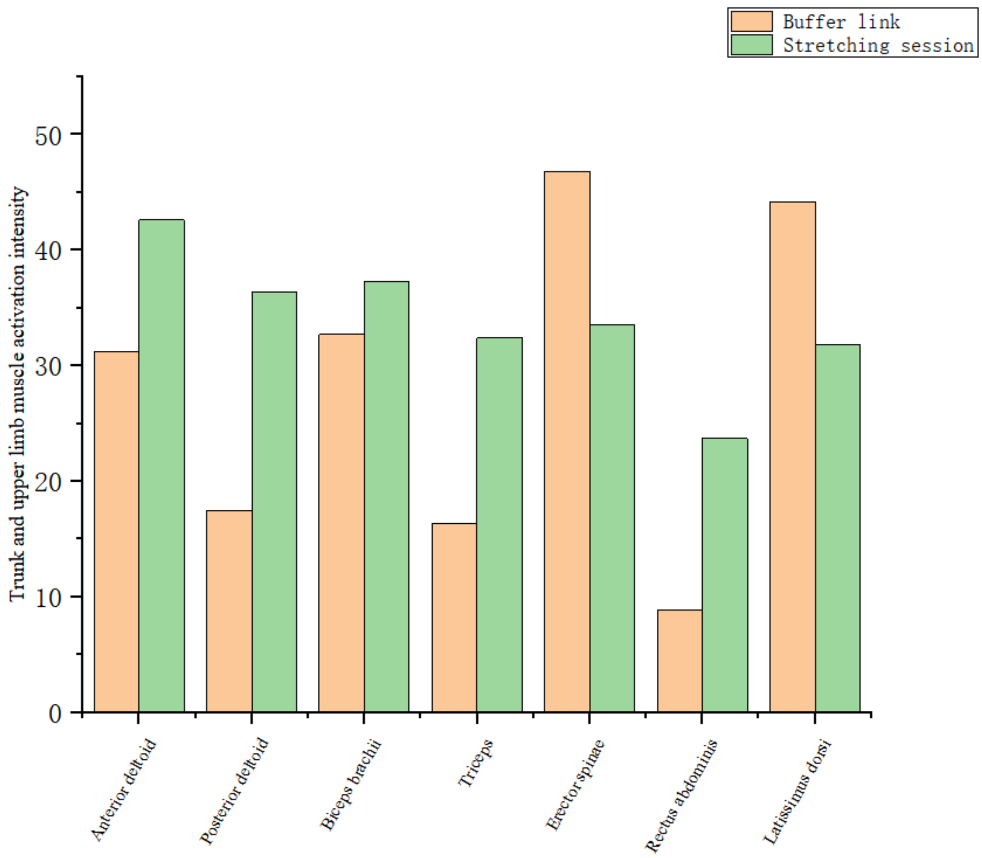

Figure 7. Activation intensity of upper limbs and trunk muscle groups in the movement patterns of approach and take-off.

The research found that training focused on physical movement functions has a significant effect on improving athletes' jumping abilities. After targeted jumping training, the athletes in the experimental group showed notable progress in aspects such as approach jumps, standing jumps, and continuous jumps, with their performance improvements being particularly prominent compared to the control group. Through dynamic analysis of the jumping movements, we clarified the important roles of trunk forward swing, extension speed, and lower limb push-off angles in approach and standing jumps. Especially during approach jumps, the swinging speed of the upper limbs and the rotation angles of the hip and knee joints in the lower limbs significantly impact overall performance. Further research on muscle activation patterns revealed the activation conditions of characteristic muscles at different jumping stages. For instance, the activation intensity of the anterior tibialis is highest during the cushioning phase, while during the push-off phase, the activation of the quadriceps, gluteus maximus, gastrocnemius, deltoid, and triceps brachii is significantly enhanced. It is noteworthy that the activation effects of the gluteus maximus and erector spinae during the approach jump phase did not meet expectations. Therefore, an in-depth analysis of sports movements from the perspective of sports biomechanics provides new insights and guidance for athletes' training, thereby enhancing training effectiveness and competitive performance.

The dynamic characteristics and muscle activation patterns revealed by this research provide new pathways for the in-depth application of sports biomechanics. Future studies can be developed along three dimensions: at the level of action mechanisms, it is necessary to construct a three-dimensional motion capture and electromyography synchronization analysis system to quantify the dynamic coupling effects of upper limb swing acceleration and lower limb joint rotation, particularly the influence mechanism of ankle dorsiflexion angle and knee flexion on the efficiency of ground reaction force transmission; at the level of neuromuscular regulation, personalized training programs based on multi-source sensing should be developed, focusing on overcoming the activation delay bottleneck of the gluteus maximus and erector spinae during the energy storage-release phase, and establishing a cross-joint force ratio model between the eccentric contraction of the gastrocnemius and the concentric contraction of the quadriceps; at the level of application expansion, systematic research on the biomechanical characteristics of different populations is needed—models can be established regarding the correlation between the degradation of balance ability in the elderly and gait stability, as well as the torque at the hip joint; clarifying the threshold distribution of jump impact stress in the growth plate area is essential during the skeletal development period of adolescents; for lower limb disabled groups, it is necessary to explore energy transfer optimization strategies—prosthetic-human interfaces. It is noteworthy that the phenomenon of gastrocnemius activation attenuation has been observed in continuous jump tests, and the potential correlation between gait freezing in Parkinson's patients and the temporal disorder of the erector spinae suggests the need to establish a cross-disease muscle fatigue evolution database. By integrating computational simulation and machine learning technologies, achieving multidimensional breakthroughs from optimizing competitive performance to maintaining human movement function can provide biomechanical basis for formulating differentiated strength training, fall prevention interventions, and rehabilitation programs, thereby constructing an intelligent diagnostic system covering competitive enhancement, health promotion, and functional compensation.

5. Conclusion

Sports biomechanics, as a comprehensive discipline, is playing an increasingly important role in enhancing human health and athletic performance. Through in-depth analysis of movement, sports biomechanics provides us with a new perspective, enabling us to understand and optimize the process of exercise more scientifically.

In the field of health, the application of sports biomechanics is not limited to the prevention and assessment of sports injuries; it also demonstrates unique value in rehabilitation therapy and the intervention of adolescent idiopathic scoliosis. Quantitative analysis of sports biomechanics indicators can effectively identify potential risk factors during exercise, assisting coaches and healthcare professionals in developing exercise programs tailored to individual needs, thereby reducing the incidence of sports injuries. In rehabilitation, through targeted training and scientific guidance, sports biomechanics provides reliable solutions for patients to regain their physical abilities, which not only aids in physical recovery but also enhances the psychological well-being of patients.

In the enhancement of athletic performance, sports biomechanics plays a crucial role. Through technical analysis and training optimization, athletes can effectively improve their competitive level. Scientific training programs and technical adjustments not only enable athletes to excel in competitions but also promote the development of scientific training concepts. Therefore, sports biomechanics is not only an analytical tool but also a means to facilitate optimal human performance.

In the future, with the continuous advancement of science and technology, sports biomechanics will exert its potential in more dimensions and provide more effective support for improving the quality of human life and exercise ability. By strengthening interdisciplinary collaboration and promoting the research and application of sports biomechanics, it is expected that healthier and more efficient ways of exercising will benefit a wide range of people.

Conflict of interest: The authors declare no conflict of interest.

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