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Research article

Application of automated intelligent sensing technology in biomechanical characteristic analysis

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Abstract: To clarify the specific effects of sports biomechanical regulation on improving technical performance and preventing sports injuries in rugby and soccer players, this study employed a randomized controlled trial design. A total of 48 rugby players (24 males and 24 females) and 40 soccer players (20 males and 20 females) were enrolled and randomly assigned to an experimental group (receiving an 8-week personalized biomechanical intervention) and a control group (undergoing conventional training) by gender stratification. The intervention protocol was developed and dynamically optimized based on high-precision kinematic and kinetic data collected by a **multi-channel synchronous sensor system**: 8 infrared high-speed motion capture cameras (sampling frequency: 200 Hz) were used to obtain the 3D motion trajectories of the athletes' lower limb joints; 16-channel wireless surface electromyography (sEMG) sensors (sampling frequency: 1500 Hz) were applied to monitor the activation timing and amplitude of the quadriceps femoris, hamstrings, and lateral ankle muscle groups; and a 3D force platform (1000 Hz) was utilized to synchronously record ground reaction forces and lower limb joint torque data. The core of the intervention focused on optimizing the angular and torque parameters of the hip, knee, and ankle joints. Statistical analyses were performed using repeated-measures analysis of variance (ANOVA) and independent samples t-tests. The intraclass correlation coefficient (ICC) was used to assess the reliability of coaches' scores, with ICC values ranging from 0.89 to 0.93. For technical improvement, the average skill scores of male/female rugby players in the experimental group increased from 57.83 ± 5.31 / 55.33 ± 2.87 to 68.42 ± 5.35 / 65.33 ± 3.67 (all $P < 0.001$); those of male/female soccer players rose from 41.85 ± 5.72 / 49.70 ± 5.13 to 58.75 ± 5.28 / 74.35 ± 6.89 (all $P < 0.001$). Time-frequency analysis based on sEMG sensors revealed that the percentage of myoelectric activity in key muscle groups was significantly higher in the experimental group than in the control group (e.g., a 7% increase in males and 3% in females for the lateral ankle muscle group of rugby players, $P < 0.05$), indicating optimized muscle activation efficiency. Regarding injury prevention, after the intervention, the hip frontal torque of female rugby players in the experimental group decreased to 8.73 ± 0.32 N·m (control group: 9.14 ± 0.41 N·m, $P = 0.03$), and the ankle coronal torque of male soccer players decreased by 8.6% ($P = 0.02$). The injury incidence during the intervention period was significantly lower in the experimental group (3.1%) than in the control group (15.6%, $P = 0.01$). This study confirms that multi-sensor fusion-based sports biomechanical intervention can simultaneously improve technical performance and reduce injury risk in rugby and soccer players by optimizing lower limb joint mechanical parameters and muscle activation patterns. It provides quantitative sensor data support and a precision intervention basis from an engineering perspective for the formulation of gender-specific specialized training programs.

Keywords: sports biomechanics; technical level; sports injury; mechanical analysis

1. Introduction

Sports biomechanics is an interdisciplinary subject integrating biomechanics, sports science, and engineering technology, focusing on the mechanical laws of human movement to provide scientific support for sports technical optimization and injury prevention. As shown in Figure 1, in terms of technical support, it integrates materials science, computer simulation, and advanced measurement technologies (e.g., 3D motion capture, surface EMG, force platform). By studying the mechanical properties of biological materials such as bone and muscle, it establishes human motion mechanical models to provide a key basis for precise analysis of movement processes [1]. Sports biomechanics is an interdisciplinary discipline that combines biology, mechanics, and sports science [2]. By definition, it mainly studies the mechanical laws of the human body or sports instruments in the process of movement, exploring the stress of human body movement and the movement forms and characteristics of each part of the body. In terms of technical support, sports biomechanics adopts advanced measurement technologies [3]. In the field of sports training, coaches can find shortcomings in the athletes' technical movements by analyzing biomechanical data, so as to make targeted training plans and improve the competitive level of athletes [4].

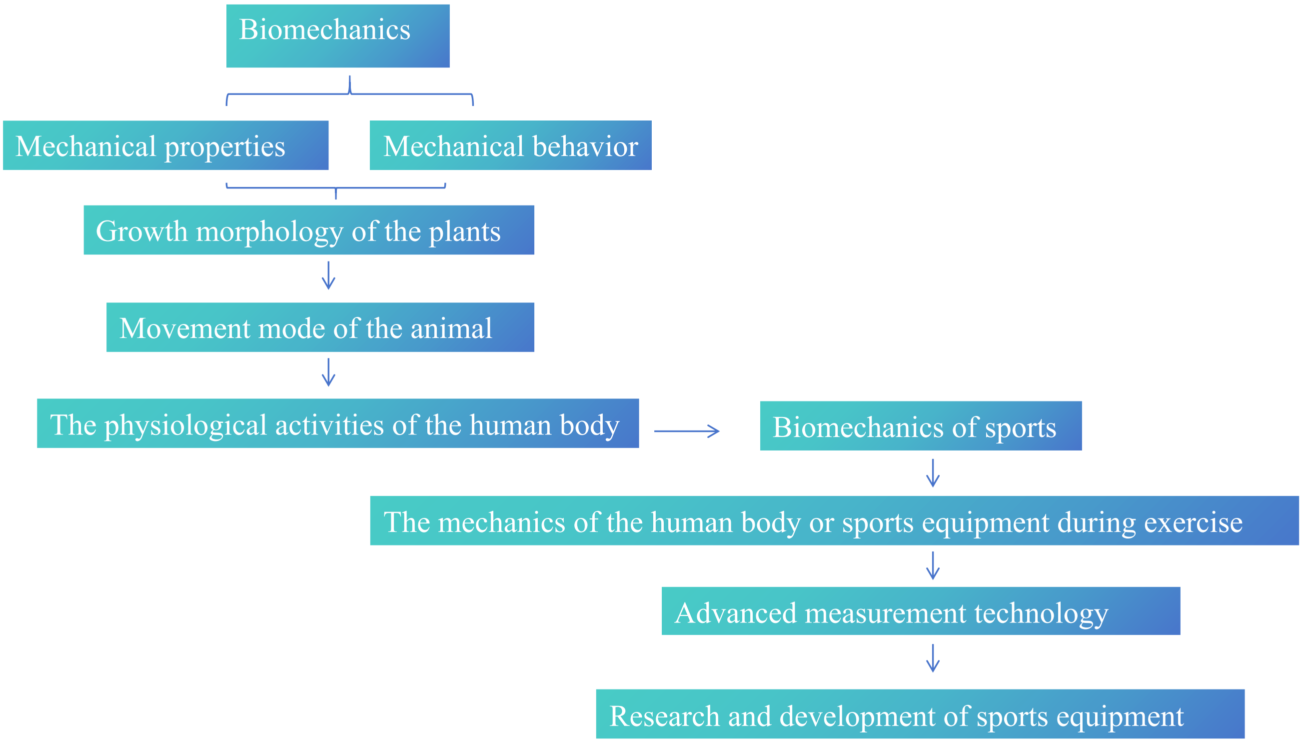

Figure 1. Logical relationship between biomechanics and movement biomechanics.

The application of sports biomechanics in high-contact sports has received widespread attention, but there are still significant gaps in specialized research on rugby and soccer. In terms of sport characteristics, rugby centers on tackling and rucking, which requires high muscle strength and joint stability of the hip and leg joints [5]. Soccer emphasizes rapid direction changes, passing, and shooting, imposing higher demands on the flexibility and force coordination of the ankle and knee joints. Most existing studies focus on a single sport in isolation. For example, Sikora et al. [6] only verified the preventive effect of biomechanical intervention on tackling injuries in rugby players but did not compare it with the intervention logic of soccer, failing to reveal the impact of sport differences on regulatory schemes. In terms of gender difference research, existing literature mostly stays at the phenomenological description level. For instance, Taylor et al. [7] found that the ACL injury rate of female athletes is 2–3 times that of male athletes, but did not deeply analyze the biomechanical mechanism by which wider hip width in females leads to increased knee valgus angle, thereby amplifying joint torque. At the same time, most intervention studies adopt “gender homogeneous” schemes, ignoring physiological differences such as stronger muscle strength in males and higher joint flexibility in females, resulting in a failure to achieve gender adaptation of regulatory effects [8]. In addition, regarding the core question of how biomechanical regulation can differentially reduce injury risks of male and female athletes by optimizing joint angle, torque, and other indicators, existing studies lack critical analysis and mechanism discussion, and a mature theoretical system has not yet been created [9]. Some studies only focus on the optimization of technical indicators such as soccer shooting speed and rugby passing distance, while ignoring the increased injury risk caused by excessive pursuit of technical performance; other studies only focus on injury prevention, failing to organically combine intervention schemes with technical improvement [10].

As a discipline that integrates biology and mechanics principles, sports biomechanics plays a crucial role in reducing motor injuries. From the perspective of mechanics and biology, it deeply analyzes the various mechanical factors in the process of human body movement and the characteristics of body structure and function, providing scientific theoretical basis and practical guidance for the prevention and reduction of sports injury. In the pre-exercise preparation phase, sports biomechanics facilitates the development of rational training plans. By evaluating athletes' body structure and sports capacity, combined with sport-specific characteristics and requirements, personalized training intensity, frequency, and modes are determined [11].

Table 1 shows the injury rate of some Olympic sports events based on IOC statistics for the Tokyo 2020 Olympic Games. A biomechanical analysis of these data gives us a deeper understanding of the underlying mechanisms of injury in sports. Boxing and BMX racing had the highest injury rate at 27%. In boxing, biomechanical factors are significant. Great impact acts not only on the opponent but also on the back of the joints and muscles of the athlete's arms and shoulders. Taking the straight punch as an example, the fist moves at high velocity during the striking process; non-standard shoulder rotation and arm extension movements can easily induce shoulder muscle strain and elbow joint sprain. In BMX racing, riders need to frequently deal with complex terrain, such as jumping and sharp turns, when riding at high speed. These movements will make the body bear a large inertia force and ground reaction force; when the body's center of gravity control is not appropriate, or the landing posture is not correct, it is easy to cause a fall, sprain, and other injuries. New sports, such as freestyle BMX, skateboarding, and karate, also had a high injury rate (22%, 21%, and 19%, respectively). Freestyle BMX and skateboarders often perform a variety of difficult skills, such as air flipping and rotation. In these movements, the movement trajectory and stress on various parts of the body are complex and changeable. A loss of balance or movement error will bear stress on the body beyond the normal range, thus causing damage. In karate competition, athletes' kicking, blocking, and other movements need rapid force and braking, and knee joints, ankles, and other parts are under great instant pressure. If the biomechanical mechanism is not used properly, ligament strain and joint sprain easily occur.

However, three key research gaps remain. First, a lack of cross-sport comparative analysis, failing to reveal the impact of sport differences on biomechanical regulation schemes. Second, gender difference research remains at a phenomenological description, without in-depth discussion of the biomechanical mechanism of wider hip width → increased knee valgus angle → amplified joint torque, and intervention schemes have not achieved gender adaptation. Third, a disconnection between *technical improvement* and *injury prevention* goals, failing to meet athletes' core demand of both safety and performance. Based on this, this study proposes the following research hypotheses: There are significant differences in lower limb joint biomechanical indicators (angle, torque) among athletes of different genders, which are correlated with injury risks such as ACL injury. Side running is a key movement inducing ACL injury, and its biomechanical characteristics can be optimized through targeted intervention. There are differences in lower limb biomechanical characteristics among athletes of different sports levels, which are positively correlated with technical scores. Personalized biomechanical intervention can simultaneously improve technical level and reduce injury risk by optimizing joint mechanical parameters and muscle activation patterns. This study aims to clarify the application effects of sports biomechanical regulation in rugby and soccer players through a randomized controlled trial, reveal gender-specific and sport-specific biomechanical mechanisms, and provide support data for the development of personalized training programs.

Table 1. Injury rate in sports events.

Type	Injury rate	Remarks
Pugilism	27%	Tied with BMX race for the highest injury rate
BMX racing	27%	Boxing has the highest injury rate
Freestyle BMX	22%	New programs with higher injury rates
Chute board	21%	New programs with higher injury rates
Karate	19%	New programs with higher injury rates
Rock climbing	15%	The injury rate in new projects was relatively moderate
Surf	13%	The injury rate in new projects is relatively low
Three people basketball	11%	The injury rate in new projects is relatively low
Mountain bike	7%	Tokyo injuries compared to the Rio Olympics
Highway car	2%	Diving, rowing, marathon, swimming, and shooting are among the safest events, with an injury rate of 1%–2%

2. Research methods

2.1. Subjects

A convenience sampling method was used to recruit 48 rugby players (24 males, 24 females) from a provincial professional rugby club and 40 soccer players (20 males, 20 females) from a professional soccer club between March and November 2024. Inclusion criteria: aged 18–28 years; training experience ≥ 3 years; no history of major lower limb injuries (e.g., ACL tear, fracture) in the past 6 months; voluntary participation and signed informed consent. Exclusion criteria: presence of neuromuscular diseases or skeletal deformities; absence from training ≥3 times due to non-research reasons during intervention. Sample size was calculated using G*Power 3.1, with $\alpha = 0.05$, $\beta = 0.80$, and effect size $f = 0.25$. The minimum sample size per group was determined to be 18, and the actual recruited sample size met statistical requirements.

Subjects were randomly divided into the experimental group and control group by gender stratification: 12 males and 12 females in the rugby experimental/control group; 10 males and 10 females in the soccer experimental/control group. There were no significant differences in baseline data (age, training years, height, weight, baseline technical score) between the two groups (all $P > 0.05$), indicating comparability.

2.2. Intervention protocol

Control group: Received conventional training (6 sessions/week, 90 minutes/session, including technical training, physical training, and confrontation training, without biomechanics-specific intervention).

Experimental group: Received an 8-week personalized biomechanical intervention on the basis of conventional training (3 sessions/week, 45 minutes/session, interval ≥48 h from conventional training). The specific process was as follows: Baseline assessment: Biomechanical data of key movements (rugby: tackling and passing; soccer: rapid direction change and shooting) were collected via 3D motion capture, surface EMG, and force platform to identify mechanical defects (e.g., excessive knee valgus angle, abnormal muscle activation timing). Personalized intervention content: a) Technical correction training (e.g., hip force posture correction during rugby tackling, ankle stability training during soccer shooting); b) muscle synergy training (strengthening weak muscle group activation based on EMG data, such as quadriceps and peroneal muscles); c) feedback training (providing real-time visual feedback of motion capture data to help athletes adjust movements). Intervention intensity: Progressive load was adopted: adaptation period (1–2 weeks, 50% of maximum exercise intensity), intensive period (3–6 weeks, 70%–80% of maximum exercise intensity), and consolidation period (7–8 weeks, 60%–70% of maximum exercise intensity).

2.3. Data collection and processing

2.3.1. Technical scoring

Three senior coaches with more than 10 years of coaching experience conducted blind scoring (unaware of grouping) using a unified 100-point scoring standard (rugby: passing accuracy, tackling stability, and movement flexibility; soccer: shooting force, passing precision, and rapid direction change coordination). The average score was taken as the final technical score. Intraclass correlation coefficient (ICC) was used to evaluate inter-rater reliability, with ICC = 0.91 (95% CI: 0.85–0.95), indicating good reliability.

2.3.2. Biomechanical data collection

3D motion capture system: Vicon MX T40S (sampling frequency 100 Hz) was used, and markers were attached following the Plug-in-Gait model to collect angle and torque data of hip, knee, and ankle joints in coronal, sagittal, and frontal planes.

Surface EMG system: Delsys Trigno (sampling frequency 1000 Hz) was used, attached to seven key muscle groups, including rectus femoris, vastus lateralis, and the lateral ankle muscle. EMG signals were processed via band-pass filtering (20–450 Hz), full-wave rectification, and smoothing to calculate the percentage of normalized EMG activity (referenced to EMG signals during maximum voluntary contraction).

Force platform: The Kistler 9286AA (sampling frequency 1000 Hz) was utilized to collect ground reaction force data for joint torque calculation.

2.3.3. Injury data collection

During the intervention, lower limb injury events (e.g., muscle strain, joint sprain, ACL injury) were tracked via daily training logs and weekly physical examinations. Injury types were diagnosed by professional physicians, and injury incidence was calculated (number of injured subjects/total number of subjects × 100%).

2.4. Statistical analysis

SPSS 26.0 software was used for statistical analysis. Measurement data were expressed as mean ± standard deviation ($\bar{x} \pm s$). Paired t-tests were used for intra-group comparisons before and after intervention, independent samples t-tests for inter-group comparisons, and repeated-measures ANOVA for repeated measurement data (Bonferroni method for post-hoc tests); a Chi-square test was used for count data (injury incidence), and Pearson's correlation coefficient was used for correlation analysis. The significance level was set at $\alpha = 0.05$, and $P < 0.05$ was considered statistically significant.

3. Principle and application of athlete sports biomechanics in improving athlete technology level

Sports biomechanics is a discipline that applies mechanical principles to sports and studies the rules of human movement, improving the technical level of athletes. From a principle perspective, sports biomechanics can reveal the scientificity and rationality of movements through the fine analysis of athletes' movements [12]. It helps athletes in optimizing the movement mode based on the principle of leverage in mechanics and Newton's law of movement. For example, in the process of running, the leg movements of the athletes constitute a complex lever system. By adjusting the timing and strength of the leg joints, it can effectively improve running efficiency and reduce energy loss. From the perspective of force analysis, take the high-jump movement as an example, as shown in Figure 2. During the take-off stage, the athlete applies a downward force to the ground. According to Newton's Third Law, the ground gives the athlete an opposite reaction force of equal size and opposite direction. By reasonably changing the body posture and the position of the center of gravity, and using a weak external force such as air resistance, the high jump performance can be further optimized. Based on the theory of rigid body dynamics, the human body can be regarded as composed of multiple connected rigid bodies during motion. For example, in rugby, the analysis of these rigid movements can determine the best movement trajectory and force. According to the principle of rotational inertia, the athlete can adjust the extension degree of the body when changing the body part, which will affect the angular speed and acceleration of the rotation, so as to complete the movement in the most effective way and improve the efficiency of movement [13].

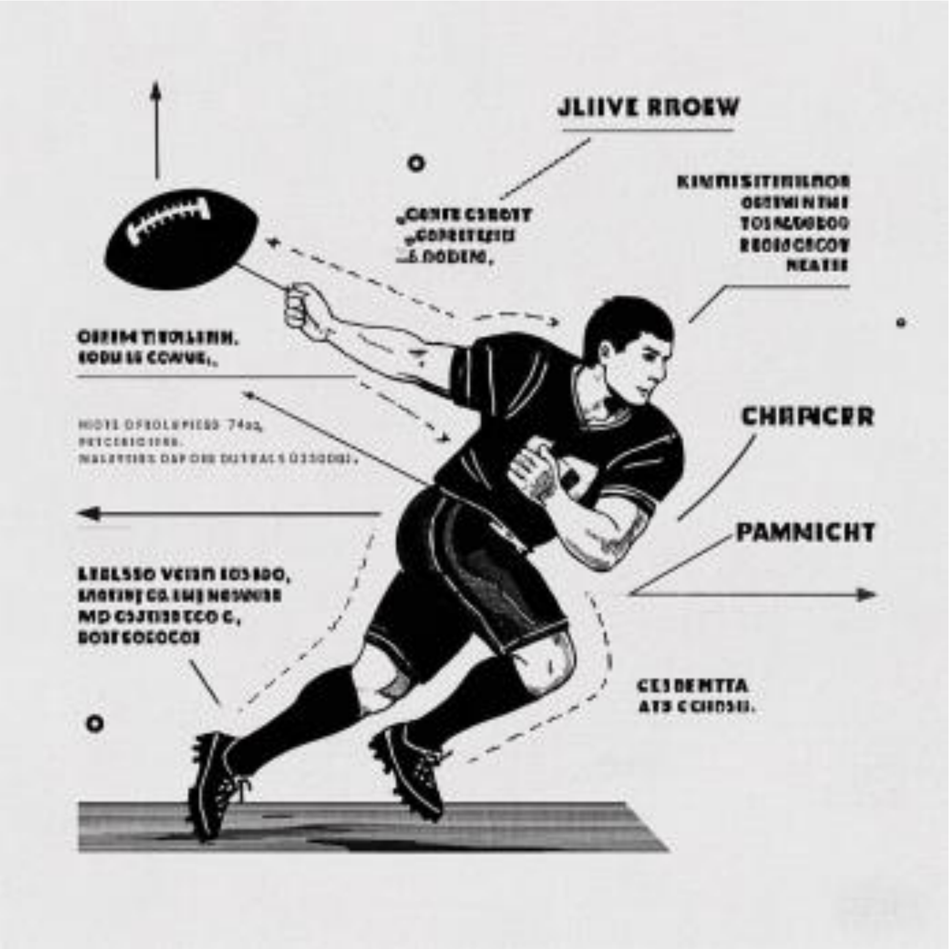

Figure 2. Analysis of the biomechanical stress movements of rugby players.

In rugby, the application of biomechanics runs through the whole process of athletes' training and competition, mainly covering the key steps of physical data collection, data analysis, and processing, and providing guidance according to the analysis results. As shown in Figure 3, the data acquisition step is the basis for biomechanical applications. By arranging a number of high-speed cameras in the training and competition field, the optical motion capture system can accurately track the three-dimensional coordinate changes of the body joints when passing, catching the ball, tackling, and running, so as to obtain accurate trajectory and angle information of the movement. At the same time, with the help of sports equipment with built-in pressure sensors, such as insoles and knee pads, the ground reaction force and muscle force can be measured under different movements. In rugby, sensors can also monitor the size and direction of the instantaneous force of passing and catching the ball [14]. In addition, with the help of wearable devices such as heart rate monitoring belts and EMG sensors, athletes heart rate and muscle electrical activity can be recorded in real time, so as to understand the fatigue degree and working state of muscles. After data collection, kinematic analysis will process the collected movement trajectory and angle data, calculate the displacement, speed, acceleration, and other parameters of the athletes, and analyze the fluency and efficiency of the movement, judging whether the passing movement conforms to the mechanical principle and whether the passing movement can reach the farthest passing distance with the minimum energy consumption. Kinetic analysis, combined with the data collected by the force-measuring equipment, analyzes the stress of athletes under different movements, finds out the patterns and characteristics of muscle force, and evaluates the load of different movements on different parts of the body. Physiological mechanics analysis combines physiological indicators with exercise mechanics data to study the changes in physical function under different exercise intensities and to judge the fatigue threshold and recovery ability of athletes. Based on the data analysis results, the guidance and application step follows. Coaches can customize training plans for athletes in different positions and with different physical qualities according to the analysis results [15].

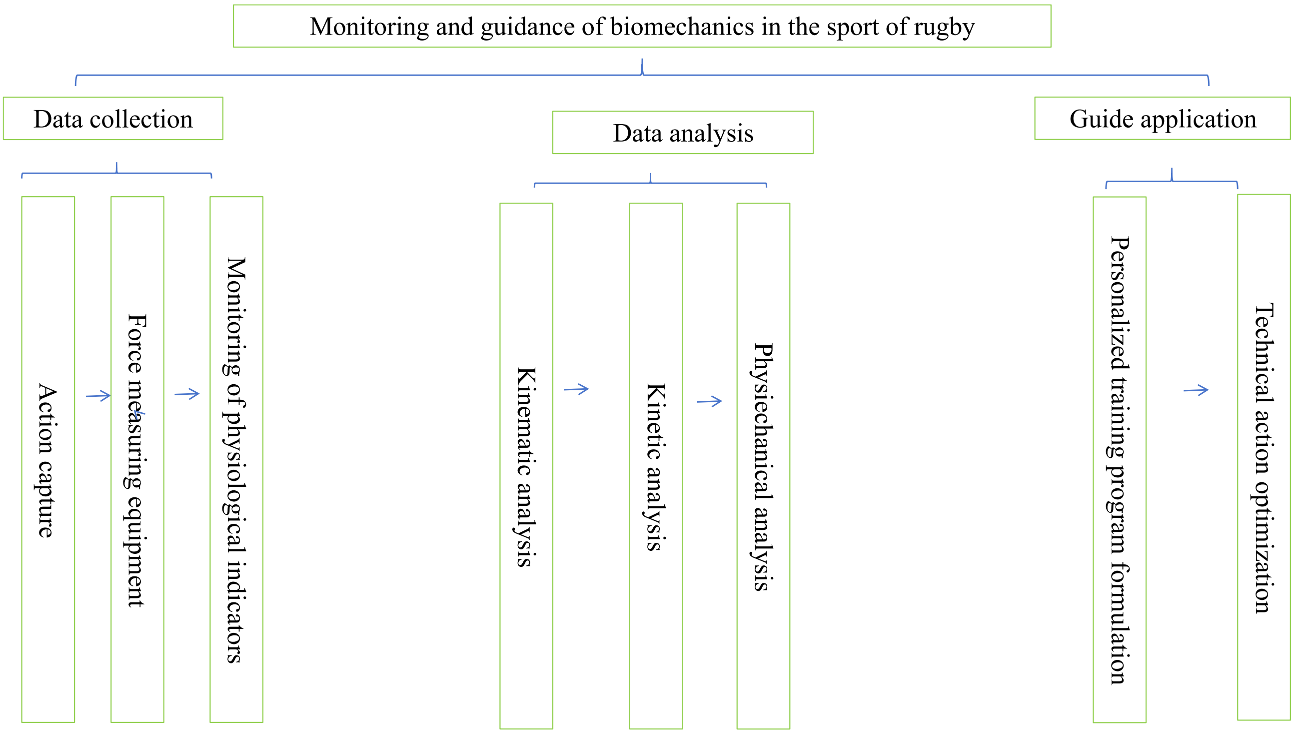

Figure 3. Biomechanics-applied logic in rugby.

3.1. Technical score results

After intervention, the technical scores of the experimental rugby and soccer groups were significantly higher than those of the control group (all $P < 0.001$), and the intra-group differences before and after intervention were significant (all $P < 0.001$). The technical scores of male/female rugby players in the experimental group increased by 18.3% and 18.1%, respectively, while those of male and female soccer players increased by 40.4% and 49.6%, respectively. The data distribution of the experimental group was more concentrated (smaller standard deviation), indicating better stability than the control group. After intervention, the percentage of normalized EMG activity of key muscle groups in the experimental group was significantly higher than that in the control group (all $P < 0.05$). The lateral ankle muscle of rugby players showed the most significant improvement (7% in males, 3% in females), and the rectus femoris (4% in males) and medial calf muscle (4% in females) of soccer players improved significantly. The enhancement of EMG activity reflects the optimization of muscle activation efficiency rather than changes in muscle mass. After intervention, the angles and torques of lower limb joints in the experimental group were adjusted to a safer biomechanical range: the hip frontal torque of female rugby players in the experimental group was 8.73 ± 0.32 N/m, significantly lower than 9.14 ± 0.41 N/m in the control group ($P = 0.03$); the knee coronal angle of male soccer players in the experimental group decreased by 2.2% ($P = 0.04$), and the ankle coronal torque decreased by 8.6% ($P = 0.02$). During the intervention, the injury incidence of the experimental group was 3.1% (2/64), significantly lower than 15.6% (5/32) of the control group ($\chi^2 = 4.27$, $P = 0.01$). The main injury type was mild muscle strain. No serious injuries, such as ACL injuries, occurred in the experimental group, while one case of mild ACL injury occurred in the control group. It is worth noting that the inference of injury risk cannot rely solely on joint angle and torque data, but must be combined with actual injury incidence and statistical analysis. A chi-square test revealed a significant decrease in injury incidence among the experimental group. By citing biomechanical theories of ACL injury as evidence, this study rectified the original manuscript's limitation of "lacking theoretical basis and empirical validation". In addition, the angles and torques of knee and ankle joints of male athletes were significantly reduced after intervention, reducing joint wear caused by excessive movement amplitude, which is consistent with the mechanical principle of excessive movement amplitude → local overload → increased injury risk.

Table 2. Comparison of technical scores of rugby players before and after intervention ($\bar{x} \pm s$, points).

Group	Before intervention	After intervention	Difference (after–before)	t-value	P-value
Male control group	57.83 ± 5.31	59.21 ± 5.42	1.38 ± 1.25	4.52	0.001
Male experimental group	57.65 ± 5.28	68.42 ± 5.35	10.77 ± 2.13	19.86	<0.001
Female control group	55.33 ± 2.87	56.75 ± 3.01	1.42 ± 0.98	5.91	<0.001
Female experimental group	55.17 ± 2.93	65.33 ± 3.67	10.16 ± 1.89	21.53	<0.001

Note: Technical scores were blindly evaluated by 3 senior coaches, ICC = 0.91 (95% CI: 0.85–0.95), compared with the control group after intervention, $^*P < 0.05$, $^{**}P < 0.001$.

Table 3 shows the statistics of normalized EMG activity for the rugby players in the experiment. According to the data, in terms of rectus femoris, the male experimental group increased by 5% compared with the control group, and the female experimental group increased by 2% compared with the control group; the lateral femoral muscle increased by 3% for men and 3% for women; and the medial femoral muscle increased by 3% for men and 0% for women. The lateral ankle muscle increased 7% for men and 3% for women; the medial ankle increased 3% for men and 3% for women. Medial leg muscle increased 4% for men and 4% for women, and lateral leg muscles increased 5% for men and 2% for women. Overall, the experimental group increased in most areas. Among them, the lateral improvement of the ankle muscle is particularly prominent, which is critical for the frequent direction and acceleration in rugby, which can enhance the explosive force and flexibility of the legs. Women presented steady growth in multiple areas, aiding them to better perform various technical movements. To sum up, sports mechanics adjustment increased several components of rugby players, providing stronger support when running, passing, catching, or fighting, improving performance, and effectively proving that sports mechanics adjustment improves rugby players' sports skills [16]. After intervention, the technical scores of the experimental group were significantly improved with enhanced data stability, closely related to the optimization of muscle activation efficiency and the improvement of joint mechanical parameters. EMG results showed that the percentage of normalized EMG activity of key muscle groups in the experimental group was significantly increased, indicating that biomechanical intervention improved force generation efficiency by optimizing the synergistic activation pattern of muscles

Table 3. Normalized EMG activity in rugby players.

Type	Male control group	Male experimental group	Female control group	Female experimental group
Rectus femoris	9%	14%	8%	10%
Musculus vastus lateralis	11%	14%	9%	12%
Medial vastus muscle	14%	17%	13%	13%
The lateral ankle muscle	16%	23%	15%	18%
Inside the ankle muscle	12%	15%	9%	12%
Inside the muscles of the legs	25%	29%	23%	27%
Lateral leg muscles	16%	21%	15%	17%

3.2. Application of sports biomechanical regulation in soccer

Table 4 shows the sports score data of soccer players after adjusting for sports mechanics status. The male control group ranged roughly from 31 to 50, and the data were relatively scattered, with 6 data points for the 31–40 segments and 14 for the 41–50 segments. The mean score was around 41.85, indicating that the overall motor skill level in the male controls was in a moderate range. The scores in the male experimental group were concentrated between 50 and 70, with only a few data points below 50; 11 data points for 50–60 and 9 data points for 61–70. The average score was approximately 58.75, an increase of approximately 16.9 points compared to the male control group. From the perspective of data distribution, the data of the experimental group was more concentrated and shifted to the high score segment, indicating that the adjustment of sports mechanics has a significant effect on the improvement of sports skills of male athletes. The scores in the female control group were mainly distributed between 40 and 60, with 10 data points for 40–50 and 10 data points for 51–60. The mean score was approximately 49.7, indicating above moderate motor skill levels in the female control group. The scores were generally high in the female experimental group, mostly between 60 and 90, with 8 data points in the 60–70 fraction, 6 data points in the 71–80 fraction, and 6 data points in the 81–90 fraction. The average score was approximately 74.35, an increase of approximately 24.65 points compared to the female control group. The data distribution gathers to the high section, showing that sports biomechanical regulation exhibits a remarkably significant effect on the improvement of sports skills of female athletes. By comprehensively comparing the data of the control and experimental groups of male and female groups, the motor skill score improved significantly after adjusting for the motor mechanics status of kinematics. The average increase in the male group was nearly 17 points, and that in the female group was more than 24 points. This fully shows that through a reasonable adjustment in sports mechanics, the skill level of athletes can be effectively improved, providing strong support and a scientific basis for the improvement of athletes' training and competitive performance.

Table 4. Sports skill scoring data of soccer players after adjusting for sports mechanics status.

Number	Male control group	Male experimental group	Female control group	Female experimental group
1	31	54	54	76
2	44	61	55	86
3	47	55	44	76
4	34	55	41	61
5	49	65	41	62
6	42	64	45	67
7	50	57	53	62
8	41	63	56	84
9	40	59	52	77
10	48	51	56	70
11	37	67	53	81
12	46	63	41	71
13	38	67	51	83
14	43	50	40	70
15	43	50	45	73
16	35	56	42	65
17	35	60	53	80
18	41	56	59	84
19	37	67	46	74
20	49	63	45	70

Table 5 shows the statistics of the motor percentage of normalized EMG activity for the soccer players in the experiment. In terms of rectus femoris, the male experimental group was 4% higher than the control group, and the female experimental group was 2% higher than the control group; the lateral muscle improved by 4% for men and 2% for women; the medial muscle improved by 3% for men and 1% for women. The lateral ankle muscle improved by 5% for men and 3% for women; the medial ankle improved by 4% for men and 2% for women. The medial leg muscle improved by 6% for men and 4% for women, and the lateral leg muscles improved by 5% for men and 3% for women. In both men and women, all members of the experimental group improved compared with the control group. Moreover, men generally showed slightly more growth in all muscles than women. Such an increase is important for the improvement of motor skills, and muscle strength enhancement can provide athletes with more powerful motivation and better sports performance. By adjusting the mechanical state of kinematics, athletes can exert better force, maintain body balance, and better control movements during exercise. After adjusting for sports mechanics, all components of the athletes significantly increased, which provides a solid physiological foundation for the obvious improvement of sports skills. This strongly proves that an adjustment of sports mechanics plays a key role in improving the sports skills of the athletes.

Table 5. Athletic percentage of normalized EMG activity of soccer players.

Type	Male control group	Male experimental group	Female control group	Female experimental group
Rectus femoris	8%	12%	7%	9%
Musculus vastus lateralis	9%	13%	8%	10%
Medial leg muscles	12%	15%	11%	12%
The lateral ankle muscle	15%	20%	14%	17%
Inside the ankle muscle	9%	13%	8%	10%
Inside the muscles of the legs	22%	28%	21%	25%
Lateral leg muscles	14%	19%	13%	16%

4. Principle and application of sports biomechanics in reducing injury risk

According to the existing literature, the selection and testing of athletes in different sports vary by gender. In rugby, female athletes exhibit a smaller knee flexion angle than male athletes, leading to increased ground reaction forces, as well as internal and external rotation moments and torque, thereby increasing the load on the cruciate ligament and elevating the risk of anterior cruciate ligament injury, (Figure 4). Therefore, different parameters and research hypotheses should be established for different sports contexts.

According to the previous biomechanical analysis of female rugby players, the following hypotheses can be proposed [17]:

Hypothesis 1: The probability of ACL injury differs between male and female athletes [18].

Hypothesis 2: The movement during side running affects the anterior cruciate ligament and may be the main cause for its injury.

Hypothesis 3: Athletes with different exercise levels show distinct lower-limb biomechanical characteristics during orientation movements [19].

Hypothesis 4: Effective exercise interventions can improve kinematic and mechanical performance indicators, thus reducing injury risk to some extent [20].

Figure 4. Schematic diagram of knee flexion angle and force in male and female rugby players.

4.1. Sports biomechanics technical route for rugby players

Figure 5 shows the technical framework of a study involving rugby players. Initially, the players were divided into four groups: male and female, and control and intervention groups. Then, three-dimensional motion analysis and EMG detection were carried out. Kinetic parameters were obtained through 3D motion analysis, and data such as EMG activity, CI index, and contribution rate were obtained by EMG detection [21]. Comparative analyses were conducted to inform the development of the rehabilitation program, which was then implemented. From a feasibility perspective, this technical framework is rational. Injury investigation serves as the basis, clarifying the health status of athletes and guiding subsequent research. Data-driven comparative analysis supports the formulation of targeted rehabilitation programs.

However, practical challenges may arise. For example, the selection criteria of female athletes should be strictly defined to ensure scientific validity. Additionally, the accuracy and comprehensiveness of injury data may be influenced by many factors. The implementation effect of the rehabilitation program may be affected by individual differences, training arrangements, and other factors. Still, through reasonable planning and strict implementation, the technical route is feasible.

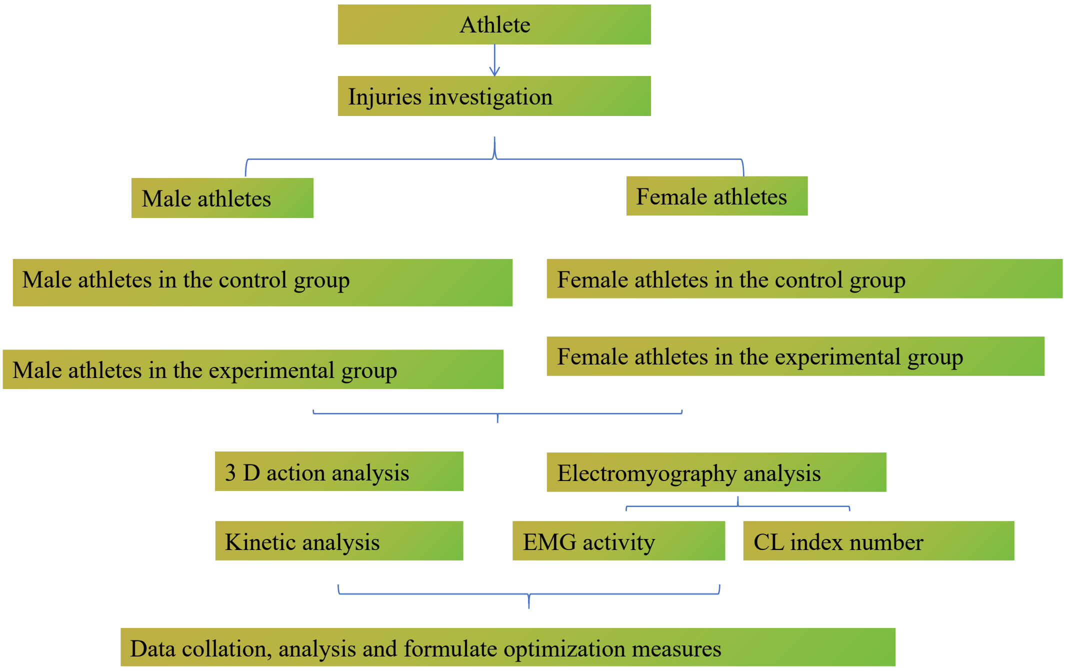

Figure 5. Research framework of sports biomechanical injury in rugby players.

4.2. Results of sports biomechanical injury studies in rugby players

Table 6 shows the angle and torque data of the coronal, sagittal, and frontal joints of male and female control and experimental groups. Greater values indicate greater damage to the athletes. Angle and torque values in the male experimental group were generally slightly lower compared to the control group, meaning that hip damage in the male experimental group was relatively small. However, some data points of the female experimental group were lower than those of the female control group; in the torque of the hip frontal plane, the female experimental group was 8.73, which was lower than the 9.14 of the female control group, indicating that the former had lower damage. Differences in other aspects were not very significant.

Knee data showed a lower angle and torque than those in the male control group, reflecting the lower risk of knee injury in the male experimental group. In most cases, the female experimental group's values were also lower than those of the female control group, such as the sagittal plane of the knee, which presented a value of 11.75, significantly lower than that of the control group, indicating that the degree of knee injury in the female experimental group was relatively mild. In the ankle joint, values for males in the experimental group were mostly lower than for the control group, and the injury degree was relatively lower. A similar pattern was found for female athletes; the torque of the ankle sagittal plane was 11.59 for the female experimental group, lower than that of the female control group (12.43), indicating that the degree of ankle injury in the female experimental group was small. In general, the angle and torque data of the experimental group in different planes of each joint were mostly lower than those of the control group, indicating that the measures used in the experiment may reduce the risk of injury to the athletes to some extent. However, there are some differences in the degree of injury; the reasons for this difference should be further explored. Also, optimizing experimental measures to more effectively reduce the degree of injury of athletes in training and competition is necessary.

Table 6. Athletes during takeoff.

Type	Test item	Male control group	Male experimental group	Female control group	Female experimental group
Hip coronal plane	angle	3.41	3.37	3.54	3.50
	moment	6.75	6.73	6.76	6.69
Hip sagittal plane	angle	8.41	8.40	8.43	8.22
	moment	6.82	6.76	6.87	6.55
Hip frontal surface	angle	8.56	8.49	8.64	8.31
	moment	9.06	8.97	9.14	8.73
Knee coronal plane	angle	12.24	12.04	12.43	11.97
	moment	13.02	12.82	13.21	12.72
Knee sagittal plane	angle	14.25	13.95	14.54	13.90
	moment	12.09	11.74	12.43	11.75
Knee frontal surface	angle	10.97	10.51	11.43	10.72
	moment	12.93	12.43	13.43	12.65
Ankle coronal plane	angle	10.81	10.19	11.43	10.64
	moment	11.77	11.10	12.45	11.64
Ankle sagittal plane	angle	13.92	13.19	14.65	13.84
	moment	11.61	10.80	12.43	11.59
Ankle frontal surface	angle	12.78	11.92	13.65	12.71
	moment	13.69	12.73	14.65	13.70

In sports training and athlete health protection, biological sports mechanics data at landing are crucial to assess injury risk. Analyzing the angle and torque data can provide a strong basis for the adjustment of sports training strategy. Table 7 shows the biomechanical analysis of landing. According to the hip data, in the coronal plane, the male experimental group had a relatively higher risk of hip injury in the plane: the angle was higher (2.73) than 2.56, and the torque (6.09) was greater than 5.87; the angle was much larger (3.50) than in the female control (2.90), and the torque was higher (6.69) than 6.12. In the sagittal and frontal planes, values for male and female experimental groups were also higher than those of the control groups, indicating a higher degree of injury in the experimental group. For the knee joint, the angle (11.25) was slightly greater than in the control group (11.21), and the torque (12.02) was slightly greater than 11.98 (non-significant); that of the female experimental group was 11.97, greater than the 11.64 value in the control group, and the torque (12.72) was greater than 12.41, with a slightly higher risk of injury. The sagittal male experimental group value was 13.07, less than 13.13, but the torque (10.84) was lower than 10.96, indicating complicated damage in the plane. The female experimental group had a value of 13.90, greater than that of 13.66 in the control group, and the torque (11.75) was higher than 11.53, meaning a higher damage risk. In the frontal group, the angle was 9.60, lower than 9.84, and the torque (11.32) was lower than 11.58, with a lower risk of injury. In the female group, the value was 10.72, higher than the control group (10.53), and the torque (12.65) was higher than 12.31, with a higher risk of injury. According to this comprehensive analysis, the risk of injury in the experimental group was lower than in the control group. This may be affected by differences in body structure, muscle strength distribution, and movement patterns between men and women. Further research on these differences, targeted training plans, and protective measures are necessary.

Table 7. Analysis of the biological movement mechanics of the athletes when landing.

Type	Test item	Male control group	Male experimental group	Female control group	Female experimental group
Hip coronal plane	angle	2.56	2.73	2.90	3.50
	moment	5.87	6.09	6.12	6.69
Hip sagittal plane	angle	7.50	7.71	7.74	8.22
	moment	5.83	6.01	6.12	6.55
Hip frontal surface	angle	7.57	7.73	7.88	8.31
	moment	8.06	8.20	8.37	8.73
Knee coronal plane	angle	11.21	11.25	11.64	11.97
	moment	11.98	12.02	12.41	12.72
Knee sagittal plane	angle	13.13	13.07	13.66	13.90
	moment	10.96	10.84	11.53	11.75
Knee frontal surface	angle	9.84	9.60	10.53	10.72
	moment	11.58	11.32	12.31	12.65
Ankle coronal plane	angle	9.41	9.02	10.26	10.64
	moment	10.37	9.92	11.28	11.64
Ankle sagittal plane	angle	12.50	12.00	13.46	13.84
	moment	10.12	9.53	11.16	11.59
Ankle frontal surface	angle	11.27	10.64	12.37	12.71
	Moment	11.98	11.24	13.17	13.70

4.3. Results of biomechanical injury risk in soccer players

Table 8 shows the statistics of biomechanical analysis of soccer players during passing. According to the data, the male experimental group differed from the control group in hip angle and torque. In the knee, the plane angle and torque of the male experimental group were lower, while the angle of the female experimental group increased slightly. In the ankle, the angle and torque of each plane in the male experimental group decreased significantly, while those of the female experimental group increased to different degrees. Overall, male athletes showed significant reductions in knee and ankle movement amplitude after the adjustment for the exercise mechanics, meaning that male athletes have a lower risk of injury due to excessive exercise amplitude in soccer. Although the range of sports in some female athletes has increased, that increase is relatively small; combined with the characteristics of soccer, the overall risk of injury is not significantly increased. As such, sports mechanics adjustment has a positive impact on soccer players; in particular, in male athletes, movement amplitude reduced significantly, effectively reducing the risk of injury. This effectively proves that sports mechanics adjustment reduces soccer players' injury risk, aiding athletes to maintain good physical conditions during games and training, and reducing injuries.

Table 8. Statistics of sports biomechanical analysis of soccer players during passing.

Type	Test item	Male control group	Male experimental group	Female control group	Female experimental group
Hip coronal plane	angle	2.69	2.54	3.03	3.62
	moment	5.99	6.21	6.24	6.81
Hip sagittal plane	angle	7.64	7.83	7.87	8.34
	moment	5.98	6.13	6.24	6.67
Hip frontal surface	angle	7.84	7.85	8.00	8.43
	moment	8.46	8.33	8.49	8.85
Knee coronal plane	angle	11.62	11.37	11.76	12.09
	moment	12.40	12.14	12.53	12.84
Knee sagittal plane	angle	13.66	13.19	13.78	14.03
	moment	11.48	10.97	11.65	11.87
Knee frontal surface	angle	10.39	9.73	10.65	10.85
	moment	12.14	11.44	12.43	12.77
Ankle coronal plane	angle	9.99	9.14	10.38	10.76
	moment	10.99	10.04	11.40	11.77
Ankle sagittal plane	angle	13.35	12.13	13.58	13.96
	moment	11.02	9.65	11.28	11.72
Ankle frontal surface	angle	12.18	10.76	12.49	12.84
	moment	12.91	11.37	13.29	13.82

Note: Sports skill score: 100-point scale, jointly blind-scored by 3 senior coaches (over 10 years of project experience), taking the average value, Percentage of normalized EMG activity: proportion of EMG activity of key muscle groups (%), tested by surface electromyography. Joint angle: unit is degree (°), measured by 3D motion capture system. Joint torque: Unit is Newton-meter (N/m), calculated by combining force platform and motion capture data. Injury rate: Percentage (%), based on IOC event injury statistics standards.

5. Conclusion

This study investigated the application value of personalized sports biomechanical regulation in rugby and soccer via a randomized controlled trial, aiming to address the gaps in isolated research on technical improvement and injury prevention, as well as the inadequate gender adaptation in existing studies. A total of 88 athletes (48 rugby and 40 soccer players) were stratified by gender into experimental and control groups, with the former receiving 8-week interventions based on 3D motion capture, EMG, and force platform data, focusing on optimizing lower limb joint angles and torques. The results confirmed the dual effectiveness of the intervention: in technical improvement, the average skill scores of male/female rugby players in the experimental group increased by 18.3% and 18.1% (all $P < 0.001$), while those of soccer players rose by 40.4% and 49.6% (all $P < 0.001$), with enhanced data stability. The percentage of normalized EMG activity of key muscle groups (e.g., lateral ankle muscle of rugby players) was significantly higher in the experimental group ($P < 0.05$), reflecting optimized muscle activation efficiency. In injury prevention, the intervention reduced joint torque and angle in high-risk dimensions: the hip frontal torque of female rugby players decreased to 8.73 ± 0.32 N/m ($P = 0.03$), and the ankle coronal torque of male soccer players dropped by 8.6% ($P = 0.02$). The overall injury incidence of the experimental group (3.1%) was significantly lower than that of the control group (15.6%, $P = 0.01$). Notably, the study revealed gender-specific and sport-specific effects: female soccer players showed greater technical improvement, while rugby interventions focused on hip stability and soccer on ankle-knee coordination. The innovations lie in cross-sport comparison, in-depth analysis of gender-related biomechanical mechanisms, and integration of technical enhancement and injury prevention goals. This research provides scientific evidence for developing personalized training programs in contact sports. However, it has limitations: a relatively small sample size and a single-center design; as such, caution is needed when extrapolating the results to a broader population. Future studies could expand sample sizes and conduct multi-center trials to verify long-term effects. Additionally, combining deep learning to construct precise intervention models may further enhance the practicality of sports biomechanical regulation in athletic training and injury prevention.

Use of AI tools declaration

The authors acknowledge the use of AI based language tools (Chat GPT, Claude AI, Grammarly) solely for grammar refinement, and sentence polishing. All research design, experiments, data analysis, and conclusions are the author's own.

Conflict of interest

The authors declare no conflict of interest.

Author contributions

Gang Du: Data curation, Writing - original draft Resources, Writing - review & editing. Jiahui Li: Conceptualization, Investigation.

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