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Computer Simulation-Based Analysis and Optimization of Sprinters' Movements

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Abstract: - Background: Sprinting is a sport that heavily relies on technical movements and explosive power. Through computer simulation technology, the analysis and optimization of sprinting techniques using biomechanics and mathematical models can theoretically provide scientific training data support, helping athletes optimize their techniques and improve their competition performance. Objective: To utilize computer simulation technology, based on biomechanics models, to analyze and optimize the technical movements of sprinters, and to propose theoretical optimization suggestions to help athletes enhance their training effects and competition performance. Methods: Conduct literature research: screen research papers related to sprinting from professional databases and journals, identifying key biomechanical variables in sprinting such as acceleration, speed, force distribution, and mechanical efficiency of movements. Based on actual movement data of athletes during the start, acceleration, and sprint phases, combined with kinematic and dynamic principles, construct a comprehensive biomechanics model considering individual differences. Use R software to create complex biomechanics models, input various movement parameters to simulate the performance of athletes under different technical movements. Conduct a detailed analysis of the simulation results, assess how different movement parameters affect the overall performance of athletes, and identify the most effective combination of technical movements. Use 3D charts and animations to visualize the simulation results, allowing coaches and athletes to intuitively see the potential effects of each technical adjustment. Results: Through simulation analysis, it was identified that acceleration phase time, maximum speed, force during the sprint phase, and starting force are the main factors affecting the 100-meter sprint performance. Optimization suggestions include high-intensity interval training, strength training, speed training, and technical optimization to help athletes improve overall performance. Conclusion: This study demonstrates the effectiveness of computer simulation technology in the analysis and optimization of sprinters' technical movements. Utilizing simulation technology for scientific and refined training can improve athletes' competitive levels and provide stronger support for their training and competition.

Keywords: Computer Simulation; Biomechanics Model; Technical Optimization; Visualization; Sports Science.

I. INTRODUCTION

100-meter sprinting is a sport that highly depends on technical movements and explosive power [1]. In a short period, athletes need to complete the 100-meter distance through precise technical movements and strong muscular explosiveness. Therefore, sprint training not only requires long-term physical conditioning and strength training but also scientific technical analysis and optimization. With the advancement of technology, the application of computer simulation technology in sprint training is becoming increasingly widespread. Through simulation technology, coaches and athletes can simulate competition scenarios in a virtual environment, analyze the details of each technical movement in detail, and optimize training programs using a data-driven approach [2]. This not only improves the scientific and targeted nature of the training but also significantly enhances athletes' competition performance.

The core of computer simulation technology lies in using biomechanics and mathematical models to accurately simulate and analyze athletes' movements. These models can construct a complete virtual sports environment based on athletes' physiological parameters and technical movement data. In this environment, every movement of the athlete can be meticulously simulated and analyzed. Simulation technology can measure and optimize key indicators such as starting angle, acceleration, step frequency, and step length, helping athletes find the technical movements that suit them best. Computer simulation technology can provide not only static analysis results but also dynamic real-time feedback, which is crucial for athletes' movement adjustments and technical improvements during training [3].

The objective of the research is to utilize computer simulation technology, based on biomechanics models, to conduct in-depth analysis and optimization of sprinters' technical movements. Through precise simulation models, athletes' performances under different training conditions can be simulated, analyzing the impact of various technical movements on competition performance, and proposing specific optimization suggestions. These optimization suggestions can help athletes improve their techniques during training and provide coaches with scientific data support to develop more reasonable training plans.

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As a sport that highly depends on technique and explosive power, sprinting can benefit from analysis and optimization through computer simulation technology, theoretically providing scientific training data support, helping athletes optimize their technical movements, and improving competition performance. The research aims to utilize computer simulation technology, based on biomechanics models, to analyze and optimize sprinters' technical movements, propose theoretical optimization suggestions, enhance athletes' training effects and competition performance, and promote better results for sprinters on the international stage.

II. RESEARCH METHODS

A. Literature Review

The research on sprint biomechanics begins with an extensive literature review to ensure the study is based on the latest scientific findings and theoretical frameworks. The research team will screen research papers related to sprinting from professional databases and journals, including studies using sports biomechanics techniques and experimental research related to sprint performance and technical optimization. By organizing these documents, researchers can identify key biomechanical variables in sprinting, such as acceleration, velocity, force distribution, and mechanical efficiency of movements, which are crucial factors in optimizing athlete performance.

B. Model Construction

Establishing a biomechanical model of sprinters is a complex task involving precise mathematical and physical analysis. The construction of the model is based on actual movement data of athletes during the start, acceleration, and sprint phases, combined with principles of kinematics and dynamics. This includes precise calculations and simulations of the movement trajectories, velocities, accelerations, and ground reaction forces of different parts of the athlete's body. The research team also needs to consider individual differences among athletes, such as weight, height, and muscle structure, which affect the model's accuracy and applicability.

Through these methods, a comprehensive biomechanical model can be constructed. This model can describe the movement characteristics of athletes during sprinting and predict the specific impact of different training methods on performance. This type of model is crucial for designing personalized training programs and technical adjustment strategies, helping coaches and athletes scientifically analyze technical movements and identify potential methods for performance enhancement.

C. Computer Simulation

Computer simulation plays a crucial role in modern sports science, especially in analyzing and optimizing the technical performance of sprinters [4]. By using powerful simulation software such as MATLAB and R, complex biomechanical models can be created, and various movement parameters can be input to simulate athletes' performance under different technical actions. These software support advanced numerical methods and algorithms, allowing precise simulations, such as adjusting starting angles, step frequency, step length, and their specific impact on speed and acceleration.

D. Parameter Analysis

The data generated by the simulation process needs further analysis to identify key factors affecting sprint performance. By detailed analysis of the simulation results, researchers can evaluate how different movement parameters impact athletes' overall performance and find the most effective combination of technical actions. This includes analyzing the optimal ratio of step length to step frequency during the acceleration phase or evaluating the specific impact of different starting techniques on final performance. This process not only helps understand the role of each parameter but also provides specific training and adjustment suggestions based on the data to help athletes improve performance.

E. Visualization

To more effectively communicate the results of the simulation analysis, visualizing the data is a very useful method. Using various computer software, including charts, dynamic simulations, and 3D animations, it is possible to intuitively show how different technical movements affect athletes' performance. This not only allows coaches and athletes to clearly see the potential effects of each technical adjustment but also helps share the research findings more broadly, allowing non-specialist audiences to understand complex biomechanical principles. These intuitive tools make it easier to identify opportunities for optimizing athletic performance, thereby formulating more effective training strategies and technical adjustments (Figure 1).

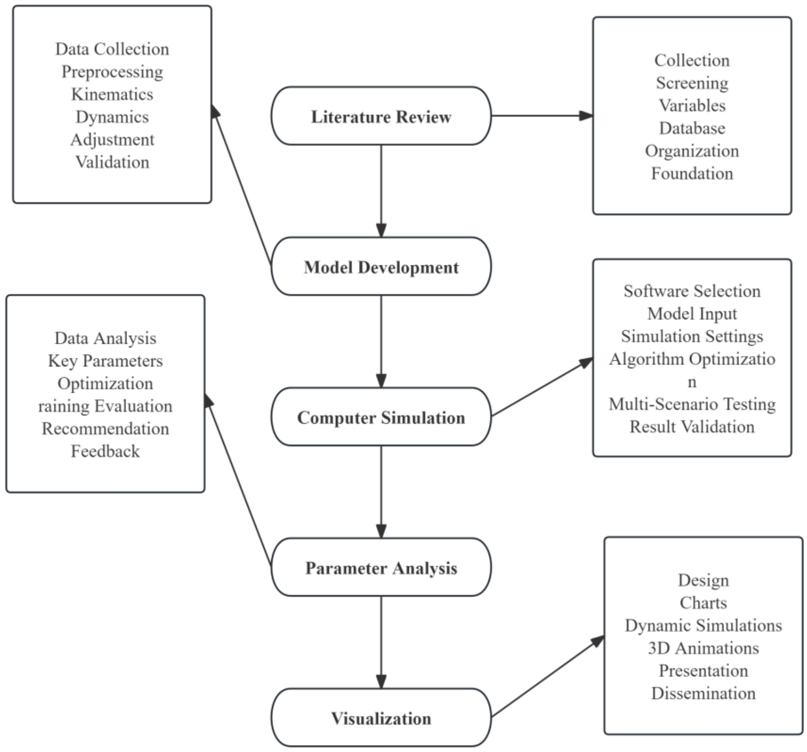

Figure 1. Research Technology Roadmap

III. ESTABLISHING THE BIOMECHANICAL MODEL

A. Starting Phase

In a 100-meter sprint, the starting phase is crucial for establishing an athlete's initial advantage. The model in this phase focuses on the initial force explosion and the generation of initial speed. The starting angle, explosive force of the legs, and ground reaction force are the main factors affecting the efficiency of the start. The ideal starting angle typically ranges between 45 to 50 degrees, which helps the athlete quickly overcome static friction and achieve initial acceleration. In this phase, the vector decomposition of forces and kinematic principles can be used to calculate the optimal value of the starting thrust. Optimizing the starting action to increase initial speed can generally be achieved by measuring the torque and leg angles during the start (Table 1).

B. Acceleration Phase

The acceleration phase transitions the athlete from initial speed to maximum speed. In this phase, increasing step frequency and step length is crucial. The model must, therefore, consider the coordinated activity of muscle groups and the gradual increase in force. The athlete's body should gradually transition from a tilted position to a near-vertical position to promote continuous speed increase. By calculating the relationship between acceleration and force, the model can determine the speed standards that must be met at different time intervals. Additionally, proper management of the center of gravity and matching step length with step frequency are parameters that must be simulated. This helps minimize air resistance and improve movement efficiency (Table 1).

C. Sprint Phase

The sprint phase typically involves the last 100 meters of the race, where the athlete needs to maintain or increase their maximum speed. In this phase, the model focuses on analyzing the dynamic and biomechanical conditions under which the athlete maintains high-speed movement. Key parameters include increasing step length while maintaining step frequency and understanding how muscles respond to rapid fatigue accumulation. The model should also incorporate fatigue management, simulating how to maintain technical efficiency and force output under extreme conditions to predict and delay the onset of fatigue (Table 1).

D. Technical Coordination

Throughout all phases, the coordination of the sprinter's technical movements is crucial to achieving their maximum potential. An effective biomechanical model should not only analyze each phase individually but also study the transitions between these phases. Particularly, the transition from acceleration to sprinting requires precise technical adjustments to maintain speed without losing efficiency. The model should also include the assessment and optimization of coordinated movements of body parts such as arm swings, leg movements, and trunk stability to ensure effective force transmission and maintenance of high speed throughout the race (Table 1).

Table 1. Models and applications at different stages

Phase Name	Mechanical Principles	Model Establishment	Formula	Practical Application
Start Phase	Initial force burst and speed generation	Consideration of starting angle, leg explosive power, and ground force	Start Force = Mass x Initial Acceleration	Optimizing starting motion by measuring torque and leg angles
Acceleration Phase	Increase in stride frequency and stride length	Coordinated activity of muscle groups and gradual increase in force	Final Speed = Initial Speed + Acceleration x Time	Managing center of gravity and matching stride length with stride frequency to reduce air resistance and increase efficiency
Sprint Phase	Maintaining or increasing maximum speed	Analysis of dynamics and biomechanics conditions for maintaining high-speed motion	Sprint Force = Mass x Maximum Acceleration	Managing fatigue, maintaining technical efficiency and power output to delay onset of fatigue
Technical Coordination	Coordinating actions in each phase to maximize potential	Study of transitions between start, acceleration, and sprint phases	No specific formula	Evaluating and optimizing the coordination of body movements, such as arm swing, leg movement, and trunk stability

E. Application of Computer Simulation in Sprint Biomechanics Model

The application of computer simulation in sports biomechanics is extremely extensive, playing a crucial role particularly in the analysis and optimization of sprinters' technical movements [5]. This technology can precisely simulate the body movements and mechanical responses of athletes during the start, acceleration, and sprint phases, providing coaches and researchers with a powerful tool to analyze movement efficiency, identify technical flaws, and propose targeted improvement measures. By integrating advanced dynamic models and actual movement data, computer simulation technology can meticulously display athletes' performances in real competitions or training.

Using advanced simulation software, researchers can adjust the sprinter's start angle, stride length, or stride frequency, and predict how these changes will affect their speed and endurance. This precise simulation not only helps understand the efficiency of athletes' movements but also predicts potential injury risks, thereby optimizing training plans and competition strategies.

Computer simulation also supports visualization technology, transforming complex data and models into intuitive charts and animations, making it easier for coaches and athletes to understand the impact of technical movements and necessary adjustments. This visualization not only enhances communication and understanding but also promotes the implementation of scientific training methods. As a part of modern sports technology, it greatly enriches the methods and tools of sports science research, demonstrating significant potential in improving sprinters' performance.

F. Construction and Optimization of Motion Models

The establishment of biomechanical models usually involves the detailed capture of athletes' movements, including key movement parameters such as stride frequency, stride length, and body posture. During the start phase of a sprint, the computer model meticulously simulates the process from the athlete's push-off from the starting blocks to full-speed running, focusing on factors like start angle, leg strength, and initial speed. Through simulation software, including MATLAB, researchers can perform simulations under different technical movement settings to explore the optimal movement combinations.

G. Parametric Simulation of Technical Movements

Once an initial movement model has been established, the next task is to simulate the athlete's performance under different technical movements by inputting various motion parameters. This process typically requires detailed adjustments and optimizations of the movement parameters to find the optimal performance. For example, by altering the body tilt angle or stride frequency during the start phase, the simulation model can predict how these changes affect the athlete's acceleration and final speed.

Table 2. Simulation calculation formula and code

Steps	Description	Calculation formula	R software code (example)
Set parameters	Define the mass, initial velocity and force parameters of the athlete.	-	mass <- 70 initial_velocity <-θ
Initialize vector	Create velocity and position vectors and store the results at each time step.	-	velocities <- numeric(length(times))
Calculate loop	Iterate each time point, adjust the acceleration according to the current stage, and calculate the velocity and position.	F=m*a V=u+at S=sθ+vt	for (i in 2: length(times)) {...}
Visualize results	Graph the changes of velocity and position over time.	-	plot (times, velocities, type = 'l')

H. Analysis and Evaluation of Results

A crucial step in sports mechanics simulation is to analyze the simulation results and compare them with actual performance. This includes a detailed analysis of the simulated data to identify key factors that may influence the athlete's performance. By analyzing the motion simulations during the acceleration phase, researchers can determine which movement parameters are critical for improving the final sprint speed, such as maximizing stride length and optimizing stride frequency.

I. Application of Visualization Techniques

To make the research results more intuitive and easier to understand, the simulation results are often presented using visualization techniques. This includes using charts, animations, and 3D models to show the dynamic changes of athletes under different technical movements. This form of presentation not only helps scientists and coaches understand the data but also allows athletes to visually see their motion simulations and potential areas for improvement.

J. Parameter Analysis

In the parameter analysis of sprint mechanics, key parameters such as initial velocity, maximum acceleration, and muscle explosiveness play a decisive role. By accurately measuring and simulating these parameters, coaches can gain a deeper understanding of an athlete’s performance and guide training to optimize performance. Initial velocity is a crucial parameter in sprints as it directly affects the athlete's starting performance and final results. Good starting technique and powerful lower limb explosiveness can significantly improve initial velocity. Through computer simulation analysis, the angle and position of the starting blocks can be finely adjusted to help athletes find the most suitable starting posture, thereby optimizing their starting speed. Maximum acceleration reflects the athlete's performance during the acceleration phase, which is usually the most critical part of a sprint race. Enhancing muscle strength and improving movement techniques can effectively increase acceleration. Computer simulation technology can simulate the specific impact of different training methods on acceleration. For example, changing training intensity and frequency, and adjusting the athlete's stride frequency and length, can visually show how these adjustments affect maximum acceleration.

Muscle explosiveness is another key indicator of a sprinter's performance, especially in the start and acceleration phases. Through computer simulations, coaches and scientists can analyze how different training modes affect muscle power output and adjust training plans to strengthen this ability. Simulations can also help predict how an athlete’s muscles will respond under specific competition conditions, such as different climates and track conditions, thereby providing a scientific basis for strategy formulation on race day.

K. Motion Optimization

In the process of optimizing sprinting techniques, computer simulation plays a central role. By simulating different combinations of motion parameters, researchers can evaluate the efficiency and effectiveness of various technical movements, providing scientific guidance and recommendations for athletes' training and competition strategies.

The optimization process begins with understanding the specific impact of each technical movement on athletic performance. This includes analyzing how starting angle, stride length, and stride frequency affect the athlete's acceleration and final speed. Through computer models, scientists can precisely simulate how changes in these parameters affect the athlete's overall performance. For example, by adjusting the starting angle, the optimal angle can be found to ensure the athlete reaches the highest initial speed in the shortest time.

Computer simulations allow coaches to experiment with the impact of different training methods on athlete performance. For instance, by increasing stride frequency training, speed improvements can be observed, but it is also necessary to assess whether this change will reduce stride length and how this trade-off affects final results. Similarly, simulating the impact of strength training for different muscle groups on explosiveness and endurance can help design more effective strength and speed training programs.

The process of optimizing movements must also consider individual differences among athletes. Each athlete has different physical conditions and technical habits, meaning that the same set of technical recommendations may not be suitable for everyone. Computer simulation technology can customize training programs based on each athlete's specific parameters. This method not only enhances the athlete's performance but also effectively reduces the risk of sports injuries, ensuring that athletes can participate in competitions in the best condition.

Computer simulation provides a scientific and systematic framework for optimizing sprinting techniques, enabling coaches and athletes to more effectively utilize data and technology to optimize training and competition strategies, achieving personalized and optimized training results.

IV. Analysis of Simulation Results

A. Identifying Key Factors

By analyzing the test data of five 100-meter sprinters, this study identifies key factors influencing sprinter performance (Table 4). These factors include starting force, acceleration phase time, maximum speed, sprint phase force, stride frequency, stride length, and 100-meter race time. Athletes with higher starting force can provide greater acceleration during the starting phase, allowing them to enter the acceleration phase more quickly. The shorter the acceleration phase time, the faster the athlete can reach their maximum speed, which is crucial for overall performance. Maximum speed is a critical indicator of sprint performance, with the included data showing this speed ranging from 10.75 m/s to 10.96 m/s. Sprint phase force directly affects the athlete's ability to maintain speed during the sprint phase, with greater sprint phase force helping athletes sustain high speeds during this phase.

Stride frequency and stride length are key factors in optimizing sprinting technique. A higher stride frequency means that the athlete can move forward at a faster rate, while a reasonable stride length helps improve running efficiency. Based on the included data, stride frequency ranges from 4.5 steps/second to 4.8 steps/second, and stride length ranges from 2.1 meters to 2.3 meters. Optimizing these factors can significantly reduce the 100-meter race time, allowing athletes to achieve better results.

Table 3. Incorporating 100m sprint performance and characteristics into the model

Athlete	Weight (kg)	Height (cm)	Start Force (N)	Acceleration Phase Time (s)	Max Speed (m/s)	Sprint Force (N)	Stride Frequency (steps/s)	Stride Length (m)	100m Time (s)
A	70	175	400	2.5	10.8	300	4.5	2.2	10.84
B	65	180	380	2.8	10.75	310	4.8	2.1	10.86
C	75	178	420	2.4	10.83	320	4.6	2.3	10.69
D	68	172	390	2.6	10.95	305	4.7	2.2	10.82
E	72	177	410	2.5	10.96	315	4.6	2.3	10.75

B. Analysis of Key Factors

By conducting 3D visualization and linear regression analysis on six key indicators (starting force, acceleration phase time, maximum speed, sprint phase force, stride frequency, stride length, and 100-meter time) of five 100-meter sprinters, we were able to identify the main factors affecting 100-meter sprint performance. Using 3D visual charts, we intuitively displayed the performance of each athlete on different indicators and showed the relationships between the data points through connecting lines (Figure 2).

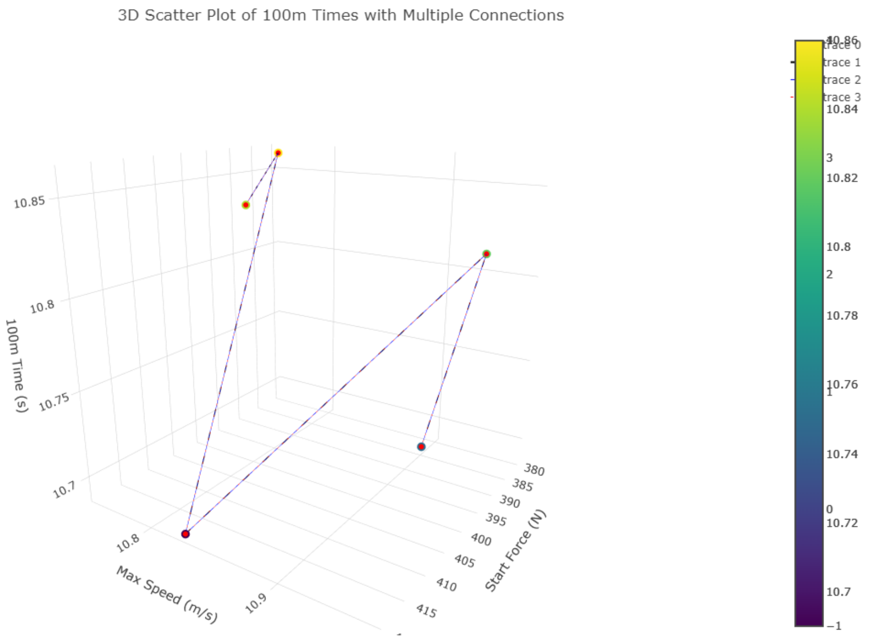

Figure 2. 3D Scatter plot of 100m Tlmes with Multiple Connectlons

According to the importance ranking of the linear regression model coefficients, the primary factors influencing the 100-meter time and their relative weights are as follows: intercept (Intercept), acceleration phase time (Acceleration_Time), maximum speed (Max_Speed), sprint phase force (Sprint_Force), and starting force (Start_Force). Specifically, the intercept has the highest weight at 10.761774194, indicating that the baseline performance has a significant impact on the 100-meter time. The weight of the acceleration phase time is 0.543548387, making it the most important dynamic factor in the model, highlighting the critical role of reducing acceleration phase time in improving overall performance. Maximum speed and sprint phase force have weights of 0.016129032 and 0.007967742, respectively. Although their weights are smaller, they still have a significant impact on the final performance. Starting force has a weight of 0.003209677, which, although relatively low, still plays an important role in the starting phase. Training can focus on optimizing the acceleration phase, reducing acceleration time, and increasing maximum speed and sprint phase force output. Additionally, optimizing starting technique can still yield subtle but important improvements.

Table 4. Variable importance scores

Variable Name	Importance Score
Intercept	10.76177419
Acceleration_Time	0.543548387
Max_Speed	0.016129032
Sprint_Force	0.007967742
Start_Force	0.003209677

V. Computer Simulation Analysis and Discussion

A. *Visualization of Simulation Results*

In the analysis and optimization of sprinters' movements, visualizing the simulation results is a critical step in transforming complex sports mechanics models into intuitive charts that are easy to understand and analyze. 3D visualization technology is particularly important because it can simultaneously display the relationships among multiple key indicators in a three-dimensional space. By plotting indicators such as starting force, acceleration phase time, maximum speed, sprint phase force, step frequency, and step length on 3D charts, we can clearly see how these factors collectively influence the 100-meter time. Using 3D scatter plots, we can show the distribution of different athletes on these indicators and use connecting lines to highlight the relationships between data points, further emphasizing the details of certain key data points. This visualization not only enhances the intuitiveness of the data but also allows coaches and athletes to more easily identify technical aspects that need improvement, providing scientific evidence for subsequent training and technical adjustments.

B. Analysis of Key Influencing Factors

After visually presenting the simulation results, the next step is to deeply analyze these results to identify the key factors that significantly affect the athletes' performance [6]. Based on the ranking results of the linear regression model coefficients, we found that acceleration phase time, maximum speed, sprint phase force, and starting force are the main factors affecting the 100-meter sprint performance of the five athletes in this study. The acceleration phase time has the greatest impact on the overall performance of the athletes, indicating that reducing acceleration time can significantly improve race results [7]. Increasing maximum speed is also crucial as it directly determines the athletes' top speed in the sprint phase. The sprint phase force affects the athletes' ability to maintain high speed in the latter part of the race, while starting force, although having a relatively smaller impact, still plays an important role in the starting phase. By analyzing these factors, we can clearly understand the specific impact of each factor on different athletes, thereby providing data support for optimizing training and technical adjustments.

C. Formulation of Training Optimization Suggestions

Based on the simulation results and the analysis of key influencing factors, we can formulate specific optimization suggestions to guide technical adjustments in actual training. To optimize acceleration phase time, high-intensity interval training and strength training can be used to enhance athletes' explosive power and acceleration ability, optimize starting posture, and improve the technical details of the first few steps to enhance overall acceleration performance. To increase maximum speed, specialized training such as overspeed training, towing runs, and resistance runs can be implemented, and coordination training for step frequency and stride length can be optimized to maintain stride length while increasing step frequency. For optimizing sprint phase force, endurance training and muscle recovery training can manage fatigue, optimize the technical movements of the sprint phase, and adjust body posture and step frequency. Optimizing starting force can be achieved through starting reaction drills and thrust training to enhance starting ability, and detailed analysis of starting movements using video analysis technology to provide personalized improvement suggestions. Integrating these optimization suggestions can help athletes make targeted technical adjustments in actual training, improve overall race performance, and continuously monitor and adjust training plans through simulation technology to ensure continuous optimization of training effects.

D. Future Development and Research Directions

The application of computer simulation technology in sports science is rapidly developing, gradually becoming a core tool for optimizing athlete performance, preventing sports injuries, and formulating training plans. With the improvement of computing power and algorithm advancements, simulation technology can handle more complex and detailed sports data, providing more accurate and comprehensive analysis. The development of real-time simulation technology allows coaches and athletes to receive immediate feedback during training, adjust technical movements and strategies. The combination of virtual reality (VR) and augmented reality (AR) technologies is also continuously innovating training methods, enabling athletes to simulate competition scenarios in virtual environments, conduct specialized training, and enhance psychological and technical abilities. The introduction of machine learning and artificial intelligence technologies has greatly enhanced the predictive and analytical capabilities of simulation technology. Through big data analysis and pattern recognition, simulation models can more accurately predict athletes' performance trends and provide personalized training suggestions. The future prospects of computer simulation technology in sports science are very promising and will continue to drive the scientific and precise development of sports training.

E. Improvement and Innovation of Simulation Technology

To better serve athletes' training and competition, computer simulation technology needs continuous improvement and innovation. First, in data collection, sensor technology development should be strengthened to improve data accuracy and reliability. For example, developing high-precision wearable devices can monitor athletes' physiological and movement data in real-time, providing richer and more accurate input for simulation models. Second, in model construction, more attention should be paid to personalization and dynamism. Each athlete's physical condition and technical characteristics are different, and personalized simulation models can better reflect their actual situation and provide targeted training suggestions. Dynamic simulation models can be updated and adjusted at any time to reflect athletes' performance in different training phases and states. Finally, in the display and application of simulation results, advanced visualization technology and user interface design should be combined to make simulation results more intuitive and understandable, facilitating analysis and decision-making by coaches and athletes. Through continuous improvement and innovation, simulation technology can more comprehensively support athletes' training and competition, enhancing their competitive level and performance.

VI. CONCLUSION

This study conducted a detailed analysis and optimization of sprinters' technical movements using computer simulation technology. By using simulation software and sports mechanics models, we accurately simulated athletes' movements at different stages and assessed the impact of various key parameters on race performance. Simulation results indicated that acceleration phase time, maximum speed, sprint phase force, and starting force are the main factors influencing sprint performance. Based on these findings, we proposed specific optimization suggestions to help athletes improve overall performance. Additionally, we visually presented the simulation results using 3D visualization, allowing coaches and athletes to more clearly understand the areas for technical improvement. With further advancements in computing power and algorithms, the application of computer simulation technology in sports science will become more widespread and in-depth, providing stronger support and assurance for athletes' training and competition. It can not only enhance athletes' competitive levels but also effectively prevent sports injuries, driving continuous progress in sports science.

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CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest to report regarding the present study.

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