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Article

Research on Technical Characteristics and Training Optimization of Starting Technique in Speed Slalom of Freestyle Roller Skating Based on Kinematics and Dynamics

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Abstract: This study investigates the starting technique in the speed slalom event of freestyle roller skating from both kinematic and dynamic perspectives, with the aim of providing a scientific basis for performance enhancement. Using a combination of literature review, controlled experiments, and mathematical statistics, the research decomposes the start into distinct phases and systematically examines key spatiotemporal and joint-angle parameters, ground reaction forces, and impulse characteristics. The technical characteristics of elite skaters are summarized in terms of body posture, center-of-mass trajectory, push-off sequence, and force application patterns. On this basis, movement norms, typical parameter ranges, and internal relationships between kinematic variables and dynamic outputs are clarified, highlighting the determinants of rapid acceleration and stability in the initial strides. Guided by these findings, targeted training content and optimization strategies are designed, including specific strength exercises, coordination drills, and start-phase simulation training that emphasize force direction, rate of force development, and technical consistency. The proposed optimization scheme is implemented in practice and its effectiveness is preliminarily verified through comparative performance tests and technical evaluations. The results indicate that structured, biomechanically informed training can significantly improve starting efficiency and technical quality in speed slalom, offering a useful reference for coaches and athletes and contributing to the scientific development and standardization of freestyle roller skating training.

Keywords: freestyle roller skating; kinematics; dynamics; training; performance; technique

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1. Introduction

Speed slalom, a sport that integrates both technical precision and competitive intensity, has witnessed significant growth on both domestic and international stages in recent years. In this discipline, the starting technique plays a pivotal role as it marks the initiation of the skating process [1]. This technique directly influences the athlete's initial speed and rhythm, which are critical for maintaining momentum and achieving optimal performance throughout the competition. A well-executed starting technique enables athletes to rapidly establish a speed advantage, providing a strong foundation for successful skating and enhancing their overall competitive edge.

At present, research on starting techniques for freestyle roller skating speed slaloms has been conducted by scholars both domestically and internationally. However, there remain gaps in the comprehensive integration of kinematic and dynamic principles, as well as in the development of tailored training programs that align with individual technical characteristics. Kinematic and dynamic analysis methods offer scientific tools for delving into the intricate details of these techniques. Kinematics focuses on studying

the motion of objects, analyzing parameters such as displacement, velocity, and acceleration. By examining these parameters, researchers can gain a clearer understanding of the trajectory and dynamic changes athletes undergo during the starting phase. Dynamics, on the other hand, investigates the interplay between motion and the forces acting upon an object, including factors such as ground reaction force and muscle strength. This approach reveals the mechanisms of force generation, transmission, and application during the starting process. By systematically analyzing kinematic parameters like displacement, velocity, and acceleration alongside dynamic factors, the underlying principles of effective starting techniques can be uncovered [2]. This study employs a multidisciplinary approach, combining literature review and mathematical statistics to analyze and interpret data. Through this comprehensive methodology, the study aims to deeply explore the characteristics of starting techniques and propose scientifically grounded strategies for optimizing training. These findings hold significant theoretical and practical value in enhancing athletes' starting techniques and advancing the scientific development of freestyle roller skating speed slaloms.

2. Kinematic Analysis of the Starting Technique of Speed Slalom

2.1. Starting Movement Phases and Key Points

Based on the professional theory and actual competition scenarios of freestyle roller skating speed slalom, the starting movement can be divided into three core phases: preparatory stance, starting push-off, and acceleration. The preparatory stance serves as the foundation of the start and has a direct impact on the power generation required for subsequent movements [3]. During this phase, the athlete should maintain a moderately low center of gravity, ensuring stability and readiness. The feet should be positioned apart, with toes pointing forward and the back foot slightly rotated outward. The knees should remain slightly bent, while the upper body leans slightly forward to optimize balance and control. Arms should be relaxed at the sides or slightly extended, and the athlete's gaze should focus on the cone group ahead. This posture ensures that the body is in an optimal state of readiness, enabling a quick and efficient start.

The initial push-off phase is a critical component of the start, as the quality of movement during this stage directly influences the athlete's initial velocity [4, 5]. When pushing off with the back foot, athletes should maximize the strength of their leg muscles, transferring force effectively to the ground through the coordinated extension of the ankle, knee, and hip joints. The push-off motion should be directed slightly forward and upward to generate both forward horizontal thrust and a degree of upward support. Simultaneously, the front foot must provide firm support to stabilize the body and prevent unnecessary swaying. During this process, it is essential to emphasize the consistency and explosiveness of the force applied, ensuring that the energy is released in a controlled and instantaneous manner. This phase lays the groundwork for achieving optimal speed and momentum.

The acceleration phase follows the initial push-off and is characterized by the athlete's continued effort to increase speed using the momentum generated. During this phase, the athlete must quickly adjust their body posture, progressively shifting their center of gravity forward to maintain stability and enhance coordination. Alternating push-offs with each foot are performed to sustain forward motion, while the stride rate is gradually increased to achieve maximum speed. The natural swinging of the arms plays a crucial role in maintaining balance and rhythm, further contributing to the athlete's overall efficiency [6]. This phase is essential for reaching a high velocity within the shortest possible time, ensuring the athlete is well-prepared to navigate through the cone group with precision and control.

2.2. Analysis of Key Kinematic Parameter Characteristics

To further investigate the kinematic characteristics of the starting technique in freestyle roller skating speed slalom, this study examined critical parameters such as displacement, velocity, acceleration, and joint angles [7]. Advanced measurement tools, including high-speed cameras and motion capture systems, were employed to collect data from both elite and average skaters during the starting phase. These tools provided precise and detailed insights into the biomechanical differences between the two groups, enabling a comprehensive understanding of their performance.

In terms of displacement parameters, elite skaters demonstrate a more pronounced and directional displacement of their rear foot during the initial push-off phase, which effectively propels their bodies forward with greater efficiency. In contrast, average skaters often exhibit insufficient displacement or a lack of directional control during push-off, which can hinder their forward momentum. Regarding velocity parameters, elite skaters are capable of rapidly increasing their gliding speed shortly after the start. Their initial speed and the rate of speed increase during the acceleration phase are significantly higher compared to average skaters. This advantage stems from their precise push-off mechanics and optimal body posture, which collectively reduce energy loss and enhance the efficiency of speed conversion [8].

Acceleration parameters provide insight into the rate of speed change. Elite skaters achieve higher acceleration values at the start, reflecting superior explosive power and the ability to quickly reach higher speeds. In terms of joint angles, elite skaters typically maintain a knee angle between 110 and 130 degrees and a hip angle between 130 and 150 degrees in the ready position. This range of angles creates an optimal biomechanical foundation for muscle contraction, facilitating efficient power generation [9]. Conversely, average skaters often adopt joint angles that are either too wide or too narrow, which can impede muscle power development and reduce overall performance. A detailed comparative analysis of these kinematic parameters highlights the characteristics of effective starting techniques, offering valuable guidance for athletes aiming to refine their skills and improve their competitive outcomes.

3. Dynamic Analysis of the Starting Technique of Speed Slalom

3.1. Force Mechanism During the Start

During the starting process of Speed Slalom in freestyle roller skating, athletes experience the influence of multiple forces, categorized as external and internal forces. External forces include friction, ground push, and air resistance, while internal forces are generated by muscle contractions. Among these, friction plays a pivotal role as it enables athletes to push off the ground and initiate forward motion. When the back foot exerts a backward and downward push against the ground, the ground responds with a forward static friction force, which propels the athlete's body forward. Ground push, defined as the force applied by the athlete's foot to the ground, is another critical factor. The magnitude and direction of this force directly determine the efficiency of the start. A greater ground push, when applied in an optimal direction, can significantly enhance forward momentum and improve performance during the initial phase of the run [9].

Air resistance, although minimal at the start of a run, becomes increasingly significant as the athlete's speed rises. To mitigate its effects, athletes can adopt a compact body posture, which reduces drag and enhances aerodynamic efficiency. Internally, the forces generated by muscle contractions are transmitted through the bones and joints to the feet, where they are converted into forces acting on the ground. During the starting and pushing phases, key muscle groups such as the quadriceps femoris and gastrocnemius work in synergy, producing powerful and explosive movements [10]. These forces exhibit dynamic variations throughout the starting phase. As the pushing action progresses, the pushing force initially increases, reaching a peak, before gradually decreasing. The friction force, closely linked to the horizontal component of the pushing force, mirrors this pattern of change. A comprehensive understanding of the principles

governing these forces and their dynamic interactions is essential for refining starting techniques and achieving optimal performance in Speed Slalom. By analyzing these biomechanical factors, athletes and coaches can develop strategies to maximize efficiency and power during the critical starting phase.

3.2. Correlation Between Kinetic Parameters and Starting Performance

Using dynamic measurement instruments such as force plates, it is possible to measure critical dynamic parameters, including force magnitude, direction, and duration during the start phase of motion. Technical factors, such as variations in push-off angles and sequences of force application, can have a profound impact on these parameters and, consequently, on the quality of the start. For instance, when the push-off angle is too small, the horizontal component of the force becomes insufficient, leading to inadequate forward momentum [11]. Conversely, if the push-off angle is excessively large, the vertical component of the force increases disproportionately, resulting in energy inefficiency and potential disruptions to body balance. These findings underscore the importance of optimizing technical execution to achieve a balanced and effective start.

Elite runners are known to identify and utilize an optimal push-off angle that maximizes the horizontal component of their push-off force, thereby ensuring a strong and efficient start. In terms of the sequence of force application, these athletes typically initiate force generation at the hip joint, followed by a coordinated extension of the knee and ankle joints [12]. This sequential transfer of force allows for a gradual accumulation and effective application of force to the ground, thereby extending the duration of force application. In contrast, average runners often exhibit a less coordinated sequence, leading to lower peak push-off forces and shorter durations of force application. This lack of synchronization can hinder their ability to achieve optimal starting performance.

The study highlights that dynamic parameters such as peak push-off force, the ratio of the horizontal force component, and the duration of force application are strongly and positively correlated with key starting performance indicators, including initial speed and acceleration post-start. By analyzing the intrinsic relationships between these dynamic parameters and starting performance, athletes can gain valuable insights into improving their push-off techniques [7]. This scientific approach provides a robust foundation for enhancing the quality of starts, enabling athletes to achieve better overall performance in competitive scenarios.

4. Technical Characteristics of Starting Process of Speed Slalom

4.1. Summary of Technical Movements and Parameter Characteristics

A comprehensive kinematic and dynamic analysis reveals that an effective freestyle roller skating speed slalom start technique demonstrates distinct characteristics in terms of technical movements and parameters. Regarding technical movements, during the preparatory phase, the body's center of gravity is maintained in a low and stable position, with the upper body leaning forward at an appropriate angle and the feet positioned optimally to ensure balance and readiness. In the initial push-off phase, the push-off action is executed smoothly and powerfully, characterized by the coordinated extension of the hip, knee, and ankle joints. The sequence of force application is precise, and the rear foot push-off direction is accurately aligned to maximize propulsion. During the acceleration phase, the body's center of gravity transitions forward promptly, with the posture remaining coordinated and the alternating push-off rhythm being quick and efficient. These movements collectively contribute to a seamless and effective start in speed slalom performance.

In terms of kinematic parameters, elite athletes typically achieve an initial velocity ranging from 2.5 to 3.5 m/s. During the acceleration phase, peak acceleration can reach values between 3 and 5 m/s². Joint angles in the preparatory position are generally maintained within a range of 110 to 130 degrees at the knee and 130 to 150 degrees at the hip, ensuring optimal biomechanical efficiency. Regarding dynamic parameters, the peak

push-off force exerted is usually between 1.5 and 2.0 times the athlete's body weight, with the horizontal component accounting for no less than 60% of the total force. The duration of force application typically spans approximately 0.3 to 0.5 seconds. By clarifying these ranges for technical movements and parameters, specific reference standards can be established to guide athletes in refining their technical training and improving overall performance in speed slalom events.

4.2. Analysis of the Inherent Correlation of Technical Features

Kinematic and kinetic parameters are deeply interconnected, with their interaction playing a crucial role in determining speed and stability control during the starting phase [13]. Kinetic parameters serve as the foundation for changes in kinematic parameters. Dynamic characteristics, such as the magnitude, direction, and duration of the ground-pushing force, have a direct impact on an athlete's kinematic performance, including displacement, velocity, and acceleration. For instance, a larger horizontal component of the ground-pushing force, combined with an optimal duration of action, allows the athlete to achieve greater acceleration. This, in turn, facilitates a rapid increase in gliding speed and displacement, which are essential for effective performance during the initial phase of motion.

Kinematic parameters also exert a reciprocal influence on kinetic parameters. Adjustments in body posture and changes in joint angles can significantly affect the efficiency of muscle force generation and its transmission. For example, maintaining appropriate knee and hip joint angles can enhance mechanical leverage for muscle contraction, thereby improving the efficiency of ground-pushing force generation [14]. During the process of increasing speed, variations in kinematic parameters alter the magnitude and distribution of external forces acting on the athlete. These changes subsequently influence the kinetic parameters, creating a dynamic feedback loop. The synergistic interaction between these two factors ensures that athletes can rapidly increase their speed while maintaining stable balance during the starting phase. This balance is critical for establishing favorable conditions for subsequent movements, such as navigating through cones or other agility-based tasks (As shown in Table 1).

Table 1. Internal correlation analysis.

Parameters	Specific parameters	Interaction with other parameters	Impact on starting performance
Kinematic parameters	Knee angle (preparatory position)	Reasonable angle (110°-130°) provides good mechanical leverage for muscle contraction and improves the efficiency of pedaling force generation	When the angle is appropriate, the muscles exert sufficient force, which helps to increase the peak force and the proportion of horizontal components, thereby increasing the initial speed and acceleration.
Kinematic parameters	Hip angle (preparatory position)	The appropriate angle (130°-150°) is combined with the knee joint angle to optimize the body's center of gravity distribution and	A reasonable angle can stabilize the body's center of gravity, reduce energy loss, ensure effective transmission of ground force, and promote speed improvement.

		enhance the stability of force generation.	
Kinematic parameters	Initial velocity	Determined by the horizontal component of the ground-pushing force and the duration of action, a higher initial speed will change the distribution of external forces such as air resistance.	It directly affects the starting point of the subsequent acceleration phase. A high initial speed makes it easier to quickly reach the ideal gliding speed.
Kinematic parameters	Acceleration	It is positively correlated with the horizontal component of the pedaling force. The greater the horizontal component of the pedaling force, the greater the acceleration	High acceleration can enable athletes to quickly increase their speed in a short period of time and shorten the acceleration time.
Kinetic parameters	Peak value of push-off force	Affected by muscle strength and joint angle, when the joint angle is reasonable, the muscle force efficiency is high and the peak force is large.	The larger the peak value, the stronger the forward momentum provided, which helps to improve the initial speed and acceleration
Kinetic parameters	Proportion of horizontal component of pushing force	It is related to the pedaling angle. When the pedaling angle is reasonable, the horizontal component accounts for a high proportion (not less than 60%).	The higher the proportion, the more effective forward momentum, the less energy wasted, and the faster the start.
Kinetic parameters	Action time of push-off force	It is related to the order of force application. The correct order of force application can prolong the action time.	Prolonged action time can make the power continue to act on the body, promote the continuous improvement of speed, and enhance the acceleration effect

5. Training Optimization Strategies for the Starting Technique in Speed Slalom of Freestyle Roller Skating

5.1. Case Analysis

A national-level speed slalom athlete encountered challenges related to maintaining a stable center of gravity and achieving efficient force transmission during the starting phase of competition. Kinematic and dynamic testing revealed specific issues in the athlete's preparatory posture. The knee joint angle was excessively large, approximately 145 degrees, which hindered the formation of an effective force-exerting lever [12]. Additionally, the hip joint angle was too small, around 120 degrees, limiting the

contraction range of the gluteus maximus. During the push-off stage, the push-off angle was inclined backward by approximately 10 degrees, resulting in the horizontal component of the push-off force accounting for only 52% of the total force. These biomechanical inefficiencies significantly impacted the athlete's starting performance.

To address these technical deficiencies, the coaching team implemented a specialized training program tailored to the technical demands of the starting phase in speed slalom. The program included targeted strength training to correct muscle imbalances. Barbell back squats were performed in three sets of ten repetitions, with the weight set at 40% of the athlete's body weight, to enhance the strength of the quadriceps femoris. Glute bridge exercises with resistance bands were conducted in four sets of fifteen repetitions to improve the contraction force of the gluteus maximus. For action standardization, the team utilized slow-motion video feedback and real-time motion capture to refine the athlete's preparatory posture. Daily 30-minute sessions were dedicated to guiding the athlete in maintaining a knee joint angle within the range of 115 to 125 degrees and a hip joint angle between 135 and 145 degrees. A laser guidance device was employed to correct the push-off direction, ensuring the push-off angle remained within the optimal range of 5 to 8 degrees forward. Additionally, rhythm control training was introduced using a metronome to establish a consistent push-off rhythm of 0.35 seconds per cycle. This approach aimed to help the athlete develop a precise and effective force-exerting sequence [4].

After ten weeks of systematic training, the athlete demonstrated significant improvements in starting technique. Retesting showed that the knee joint angle stabilized at 120 degrees, while the hip joint angle reached 140 degrees during the preparatory posture. The horizontal component of the push-off force increased to 65%, and the peak push-off force rose to 1.8 times the athlete's body weight. Additionally, the force action time extended to 0.42 seconds, and the initial starting speed improved from 2.3 meters per second to 3.1 meters per second. These advancements provided the athlete with a clear advantage during the initial stages of races. At the 2024 National Freestyle Roller Skating Speed Slalom Championships, the athlete's optimized starting technique contributed to a dominant performance, culminating in a championship victory in the men's senior group. This achievement marked a significant milestone in the athlete's career and underscored the effectiveness of training optimization strategies based on kinematic and dynamic technical analysis in addressing specific performance challenges and enhancing competitive outcomes.

5.2. Training Content Design Based on Technical Characteristics

Based on the technical characteristics of the speed slalom starting technique outlined above, targeted training content has been developed to address the monotony and lack of specificity often encountered in traditional training methods. Specific strength training serves as a critical foundation for enhancing starting ability, with a focus on improving the strength and explosiveness of the leg muscles. Exercises such as squats, lunges, and heel raises are recommended, and these can be augmented with resistance bands to introduce additional resistance, thereby enhancing muscle contraction force and speed. Core strength training is equally prioritized to improve stability and balance, which are essential for effective power transmission during the start phase. This comprehensive approach ensures that athletes build a robust physical foundation tailored to the demands of speed slalom performance.

Standardized movement training is designed to help athletes achieve mastery of correct starting mechanics. By breaking down the movements into distinct phases, athletes can identify and correct errors in their preparatory stance, initial push-off, and acceleration phase. Techniques such as slow-motion exercises and mirror feedback are employed to enable athletes to observe and refine the intricate details of their movements, fostering the development of accurate and efficient movement patterns. Additionally, rhythm control training is incorporated to enhance coordination and timing. This involves the use of rhythmic signals, such as metronomes or verbal cues, to guide athletes in

synchronizing their push-off timing and stride frequency. By improving rhythm and coordination, athletes can more effectively convert their physical force into forward momentum, optimizing their performance during the start.

5.3. Innovative Application of Training Methods and Means

Introducing innovative training methods and leveraging technological advancements can significantly optimize training processes and improve the scientific rigor and effectiveness of athletic preparation. For instance, virtual reality training technology offers the ability to simulate realistic competition scenarios, enabling athletes to practice starting blocks in a controlled virtual environment. By incorporating visual and auditory feedback, this technology enhances athletes' adaptability and reaction times. Furthermore, athletes can repeatedly practice starting techniques under varying cone distances and diverse venue conditions within these virtual scenarios, allowing them to accumulate valuable competition experience and refine their skills in a risk-free setting.

Personalized intelligent training equipment, such as wearable sensors and advanced data analysis systems, plays a crucial role in modern athletic training [1, 9]. These tools collect real-time kinematic and kinetic data from athletes during their starting movements, providing a detailed understanding of their performance. Sophisticated data analysis software processes this information to generate comprehensive and personalized training assessment reports. These reports enable coaches to pinpoint specific technical deficiencies in athletes' performance. Based on this feedback, coaches can design highly targeted and individualized training plans, ensuring that each athlete receives tailored guidance to address their unique needs and optimize their performance potential.

6. Conclusion

This study thoroughly analyzed the kinematic and dynamic characteristics of the starting technique for speed slalom in freestyle roller skating. Key movements during the preparatory stance, push-off, and acceleration phases were identified, along with the appropriate ranges for critical parameters such as displacement, velocity, acceleration, joint angle, and push-off force. The findings revealed a strong internal correlation between kinematic and dynamic parameters, which synergistically enhance speed improvement and stability control during the starting phase. Based on these insights, targeted training programs were developed, incorporating specialized strength training, movement standardization training, and rhythm control training. Additionally, innovative methods such as virtual reality training and personalized intelligent training equipment were introduced, forming a comprehensive and systematic training optimization strategy. These advancements not only improve athletes' starting techniques and competition performance but also highlight the potential for integrating technology into sports training. Future research could explore the long-term effects of these strategies and their adaptability across different skill levels and disciplines, paving the way for broader applications in athletic performance enhancement.

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