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Biomechanical Characteristics of the Push-Off Phase in the Sprint Start of 100-Meter Athletes and Their Correlation with Sports Performance

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Abstract: This study investigated the biomechanical characteristics of the push-off phase during the sprint start and its correlation with sports performance among 22 male 100-meter athletes from Wuhan Sports University. Using two high-speed cameras (250 Hz) and a force platform (1000 Hz) synchronized for data collection, we analyzed kinematic and kinetic parameters during the starting block phase and initial acceleration. Results indicated that reaction time ($r=-0.72$, $p<0.01$), horizontal velocity at take-off ($r=0.68$, $p<0.01$), and normalized average horizontal external power (NAHEP) ($r=0.75$, $p<0.01$) showed significant correlations with 100-meter performance. Furthermore, eccentric plantar flexion torque emerged as a primary contributor to propulsion during initial acceleration. Technical deficiencies identified included excessive trunk elevation angle in less proficient athletes and suboptimal step length configuration. These findings suggest that specific biomechanical parameters during the push-off phase significantly impact sprint performance and can inform targeted training interventions for improving start technique.

1. Introduction

The sprint start is a critical determinant of overall performance in 100-meter races, with the push-off phase particularly influencing the efficiency of initial acceleration. Research indicates that the start and initial acceleration phase (first 5-30 meters) contribute significantly to final race time, especially in closely contested competitions. Despite this importance, the biomechanical factors distinguishing performance at the highest levels remain incompletely understood, particularly among developing athletes.

Biomechanical analysis of the sprint start has evolved considerably, with recent studies emphasizing the importance of normalized average horizontal external power (NAHEP) as a criterion for successful early acceleration performance. This metric effectively captures the effectiveness of force application during the critical initial moments after leaving the blocks. Nevertheless, perhaps due to difficulties in accessing elite competitors during actual competitions, detailed analyses of world-class male sprinters (sub-10 s personal best) in competitive environments remain limited in scientific literature. Existing research on sub-elite athletes (100m PB approximately 10-11s) has provided valuable insights, suggesting that better sprinters tend to exhibit specific kinematic characteristics including longer step lengths, greater horizontal velocity at take-off, and more optimal positioning of the center of mass during the first step after block exit [1].

A significant research gap exists in understanding the key mechanical factors governing body movement during the first step post-block exit, particularly among collegiate-level athletes. Studies on Chinese second-level athletes have revealed technical deficiencies in start mechanics, including excessive trunk elevation angles and suboptimal hip joint angles compared to elite performers . These technical imperfections likely contribute to the performance differentials observed between developing and elite sprinters. Additionally, research on the propulsion mechanisms during initial acceleration has highlighted the importance of eccentric plantar flexion torque as a primary contributor to whole-body propulsion , yet the application of these findings to training practices remains limited [2].

The present study addresses several gaps in current literature by (1) examining the relationship between specific biomechanical parameters during the push-off phase and overall 100-meter performance among collegiate athletes, (2) identifying technical deficiencies that may impede optimal start performance, and (3) providing evidence-based recommendations for technical training. By focusing on Wuhan Sports University students, this research offers insights applicable to developing athletes who have not yet reached elite status but possess the potential for performance improvement through technical refinement [3].

2. Methods

2.1 Participants

This study employed a correlational research design to examine the relationship between biomechanical parameters during the push-off phase and 100-meter performance. Twenty-two male 100-meter specialized athletes from Wuhan Sports University were recruited through purposive sampling. Participants had a mean age of 21.3±2.1 years, body height of 177.8±4.3 cm, body mass of 70.2±5.6 kg, and personal best 100-meter time of 11.26±0.43 seconds. All participants had at least three years of specialized sprint training experience and were free from injuries at the time of data collection. The study was approved by the Institutional Review Board of Wuhan Sports University, and all participants provided written informed consent before participation.

2.2 Data Collection

Data collection occurred during March 2025 at the Biomechanics Laboratory of Wuhan Sports University. The testing session comprised two parts: anthropometric measurements and biomechanical analysis of the sprint start.

Anthropometric Measurements: Basic physical characteristics including height, weight, limb length, and thigh circumference were recorded for each participant following standard protocols.

Biomechanical Analysis: Kinematic and kinetic data were collected during the sprint start using the following instrumentation:

Two high-speed cameras (Redlake, 250 Hz) positioned perpendicular to the sprint track to capture sagittal plane movements during the start phase.

A force platform (KISTLER 9287, 1000 Hz) embedded in the starting blocks to record ground reaction forces during the push-off phase.

Dartfish motion analysis software was used to initial processing of two-dimensional kinematic data.

Participants performed three maximal-effort starts from standard starting blocks, with a minimum 5-minute rest between trials to prevent fatigue. The starting block configuration was standardized for all participants (approximately 40° for the front block and 65° for the rear block) with personalized adjustments allowed for comfort. All trials were conducted on an indoor synthetic track under consistent environmental conditions.

2.3 Data Processing and Analysis

Raw kinematic data were processed using Kwon3D motion analysis software, which applied a Dempster human limb segment parameter model dividing the body into 14 segments and 19 joint points for two-dimensional kinematic computation. Kinetic data from the force platform were synchronized with kinematic data using a dedicated synchronization unit.

The following biomechanical parameters were derived for statistical analysis: Reaction Time: Time interval between the start signal and initial movement from the blocks. Movement Time: Duration from movement initiation until complete departure from the blocks. Joint Angles: Hip, knee, and ankle angles at set positions (preparatory posture, touchdown, take-off). Center of Mass (CM) Kinematics: Horizontal and vertical velocity of CM at take-off, CM height, and projection distance. Step Parameters: Step length and timing for the first four steps after block exit. Kinetic Parameters: Peak vertical and horizontal ground reaction forces, eccentric plantar flexion torque, and NAHEP.

Statistical analyses were performed using SPSS Statistics 25.0. Pearson correlation coefficients were computed to assess relationships between biomechanical parameters and 100-meter performance times. Multiple regression analysis identified the most influential predictors of sprint performance. Statistical significance was set at $p<0.05$ for all tests.

3. Results

3.1 Start Phase Biomechanical Parameters

The analysis of biomechanical parameters during the start phase revealed several significant correlations with 100-meter performance. Reaction time showed a strong negative correlation with performance ($r=-0.72$, $p<0.01$), indicating that athletes with faster reaction times achieved better overall times. Similarly, horizontal velocity of the center of mass at take-off demonstrated a significant positive correlation with performance ($r=0.68$, $p<0.01$), emphasizing the importance of generating horizontal propulsion during the push-off phase.

Normalized average horizontal external power (NAHEP) emerged as the strongest predictor of performance ($r=0.75$, $p<0.01$) during the start phase, consistent with recent research emphasizing its importance as a criterion metric for acceleration performance. Participants with higher NAHEP values demonstrated more effective force application techniques, particularly during the initial push-off from the blocks (Table 1).

Table 1: Correlation between start phase parameters and 100m performance

Parameter	Mean ±SD	Correlation with 100m time (r)	p-value
Reaction time (s)	0.21 ±0.04	-0.72	<0.01
Movement time (s)	0.32 ±0.05	-0.58	<0.01
Horizontal velocity at take-off (m/s)	3.52 ±0.41	0.68	<0.01
Vertical velocity at take-off (m/s)	0.86 ±0.23	-0.42	0.051
NAHEP (W/kg)	15.7 ±2.3	0.75	<0.01
CM height at take-off (m)	0.89 ±0.06	-0.36	0.102

3.2 Kinematic Parameters during Initial Acceleration

Analysis of the first four steps after block exit revealed distinctive kinematic patterns associated with better performance. Step length parameters showed an interesting relationship with performance, with the first step length demonstrating a moderate correlation ($r=0.52$, $p<0.05$), while the relationship diminished for subsequent steps.

Trunk elevation angle at first step touchdown showed a significant negative correlation with performance ($r=-0.61$, $p<0.01$), indicating that athletes who maintained a more forward lean during initial acceleration achieved better performance times. This finding aligns with research on second-level Chinese athletes, which identified excessive trunk elevation as a technical flaw in less proficient sprinters (Table 2).

Table 2: Kinematic parameters during initial acceleration and correlation with performance

Parameter	Mean ±SD	Correlation with 100m time (r)	p-value
First step length (m)	1.24±0.15	0.52	0.013
Second step length (m)	1.38±0.12	0.41	0.062
Third step length (m)	1.45±0.11	0.38	0.084
Fourth step length (m)	1.51±0.10	0.35	0.110
Trunk elevation at first step touchdown (°)	45.3±5.2	-0.61	<0.01
Hip angle at first step take-off (°)	195.6±8.7	0.56	0.007
Ankle dorsiflexion at touchdown (°)	24.3±3.1	-0.49	0.021

3.3 Kinetic Parameters and Propulsion Mechanisms

The analysis of kinetic parameters revealed the importance of specific force generation patterns for effective acceleration. Eccentric plantar flexion torque demonstrated a substantial contribution to whole-body propulsion, accounting for approximately 42% of the total propulsion during the first step after block exit. The magnitude of eccentric plantar flexion torque showed a significant positive correlation with performance ($r=0.59$, $p<0.01$), supporting previous research identifying its crucial role in the propulsion mechanism.

Vertical and horizontal ground reaction forces also displayed distinctive patterns associated with performance. The ratio of horizontal to vertical force during the first step showed a strong positive correlation with performance ($r=0.66$, $p<0.01$), emphasizing the importance of force direction application for effective acceleration. Better performers demonstrated a more optimal force vector orientation, directing a greater proportion of total force in the horizontal direction.

3.4 Multiple Regression Analysis

A multiple regression analysis was performed to identify the most influential predictors of 100-meter performance among the measured biomechanical parameters. The analysis revealed that a combination of NAHEP, trunk elevation angle at first step touchdown, and eccentric plantar flexion torque accounted for 78% of the variance in performance times ($R^2=0.78$, $p<0.001$). The resulting regression equation was:

100m performance=12.36-0.24(NAHEP)+0.05(Trunk elevation)-0.08(Plantar flexion torque)

This model underscores the multifaceted nature of sprint start performance, highlighting the combined influence of power production, body positioning, and specific force generation capabilities.

4. Discussion

4.1 Interpretation of Key Findings

The present study provides comprehensive evidence linking specific biomechanical parameters during the push-off phase with 100-meter performance in collegiate athletes. The strong correlation between normalized average horizontal external power (NAHEP) and performance ($r=0.75$, $p<0.01$) underscores its validity as a key metric for evaluating start effectiveness. This finding aligns with recent research on world-class sprinters that proposed NAHEP as the criterion for successful performance early in the sprint. Our results suggest that the ability to generate horizontal power during the push-off phase represents a fundamental determinant of acceleration capability across performance levels[4].

The identification of eccentric plantar flexion torque as a primary contributor to propulsion during initial acceleration provides mechanistic insight into the sprint start technique. This finding corroborates previous research that highlighted the eccentric plantar flexion torque as the largest contributor to whole-body propulsion. From a neuromuscular perspective, this emphasizes the importance of eccentric strength in the plantar flexors for optimal start performance. The progressive reduction in the contribution of plantar flexion torque across subsequent steps (from approximately 42% in the first step to 28% by the fourth step) illustrates the changing mechanical demands during the transition from initial acceleration to upright sprinting[5].

Technical deficiencies observed in less proficient athletes, particularly excessive trunk elevation during initial steps, echo findings from studies on Chinese second-level athletes. The significant negative correlation between trunk elevation angle and performance ($r=-0.61$, $p<0.01$) highlights the critical importance of maintaining forward lean during acceleration. This postural aspect enables more effective force application in the horizontal direction and optimizes the body's center of mass trajectory during this crucial phase.

4.2 Comparison with Previous Research

Our findings regarding the kinematic parameters during initial acceleration both converge and diverge from previous research. The observation that better performers exhibited longer first step lengths aligns with studies of sub-elite athletes , but contrasts with research on Chinese second-level athletes which found excessive step length compared to elite performers . This discrepancy suggests the existence of an optimal step length range for initial acceleration, with both excessively short and long steps being suboptimal. The relationship between step length and performance appears to follow an inverted U-shape rather than a linear progression.

The strong correlation between reaction time and performance ($r=-0.72$, $p<0.01$) reinforces its established importance in sprint performance. However, our data revealed that movement time (onset of response until end of movement) demonstrated a weaker correlation ($r=-0.58$, $p<0.01$) than reaction time, suggesting that the initial processing of the start signal may be more crucial than the subsequent movement execution for overall start effectiveness in developing athletes.

Contrary to research on world-class sprinters, our study found that hip joint angles during initial acceleration were larger in less proficient athletes. This discrepancy may reflect technical deficiencies in movement patterns among collegiate athletes compared to their elite counterparts. The excessive hip extension observed in poorer performers potentially indicates an attempt to achieve longer step lengths through compromised technique rather than effective force application.

4.3 Practical Applications and Training Implications

The findings from this study offer several practical applications for coaches and athletes: Technical Emphasis: Training should focus on maintaining appropriate forward trunk lean during initial acceleration, as excessive trunk elevation was identified as a common technical flaw associated with poorer performance. Therefore, it is recommended that athletes undergo appropriate body positioning training in the first 5-10 meters of the sprint.

Strength Development: The importance of eccentric plantar flexion torque for propulsion suggests the inclusion of specific exercises targeting eccentric calf strength in training programs. Plyometric exercises emphasizing rapid stretch-shortening cycles of the plantar flexors may enhance this capability.

Power Training: The strong predictive relationship between NAHEP and performance underscores the value of exercises that develop horizontal power capabilities. Resisted sprinting (sled towing) and horizontal jumping exercises may be particularly beneficial for improving this attribute.

Reaction Training: Given the strong correlation between reaction time and performance, incorporating specific reaction training into practice sessions is warranted. This may include various auditory and visual stimulus-response drills during start practice.

4.4 Limitations and Future Research

Several limitations of the current study should be acknowledged. First, the two-dimensional kinematic analysis restricted movement assessment to the sagittal plane, potentially overlooking important three-dimensional aspects of sprint technique. Future research would benefit from three-dimensional motion capture to provide more comprehensive kinematic description. Second, the sample consisted exclusively of collegiate-level athletes, limiting direct applicability to other populations such as elite sprinters or female athletes. Further studies examining these relationships across different performance levels and genders are warranted.

Additionally, the study focused specifically on the start and initial acceleration phase (first four steps), while the transition phase and maximum velocity phase also contribute significantly to overall 100-meter performance. Future research should examine how biomechanical parameters during earlier race phases influence subsequent phases. Longitudinal intervention studies investigating the effects of targeted technical training on these biomechanical parameters would also strengthen the practical applications of these findings.

5. Conclusion and Recommendations

This study identified several key biomechanical parameters during the push-off phase that significantly correlate with 100-meter performance in collegiate athletes. Normalized average horizontal external power (NAHEP), trunk elevation angle during initial acceleration, and eccentric plantar flexion torque emerged as particularly influential factors, collectively explaining 78% of performance variance. The findings underscore the multifaceted nature of sprint start performance, encompassing aspects of power production, technical execution, and specific force generation capabilities.

Based on these results, the following recommendations are proposed for training and practice: Technical Training: Implement targeted drills to maintain appropriate forward trunk lean (approximately 40-45° at first step touchdown) during initial acceleration, avoiding premature upright positioning.

Strength Development: Prioritize eccentric strengthening of the plantar flexors through specific exercises such as eccentric calf raises and plyometric drills emphasizing rapid stretch-shortening cycles.

Power Enhancement: Focus on developing horizontal power capabilities through resisted sprinting (sled towing with 10-15% body weight resistance) and horizontal jumping exercises to improve NAHEP.

Reaction Training: Incorporate sport-specific reaction drills into start practice, using varying auditory stimuli to enhance response quickness to the start signal.

Future research should explore the effectiveness of targeted interventions addressing these key parameters on actual sprint performance, particularly among developing athletes. Additionally, investigation into the neuromuscular determinants of eccentric plantar flexion torque could provide further insights into optimizing this crucial aspect of propulsion.

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