

Article

Comparative Study of the Sprint Start Biomechanics of Men's 100 m Athletes of Different Levels

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Abstract: Background: This study sought to investigate the kinematic and kinetic differences in sprint start between high-level and medium-level sprinters. Methods: Twenty male sprinters were dichotomized according to their personal 100 m performance. Each sprinter performed three block starts. Six high-speed cameras were used for 2D kinematic analysis, and kinematic and dynamic forces were determined by Kisprint. Results: There was no significant differences between high-level and medium-level athletes in the antero-posterior distance of two blocks, block inclination, reaction time, push time, and the joint angle of set position ($p > 0.05$). The ankle angle of the front leg and swinging leg at the time of front leg exit were significantly greater in high-level athletes than in medium-level athletes ($p < 0.05$). The vertical RFD (rate of force development) and RFD of high-level athletes were significantly lower than that of medium-level athletes ($p < 0.05$). The relative maximum horizontal force generated by the front leg of high-level athletes was significantly larger than that of medium-level athletes ($p < 0.05$), and the maximum vertical force of the rear leg was significantly lower than that of medium-level athletes ($p < 0.05$). Conclusions: Our finding shows that the start kinematics of high-level sprinters is characterized by a greater ankle angle of the swinging leg and front support leg at the front block exit. High-level sprinters generate greater maximum horizontal force in the front block and smaller maximum vertical force in the rear block.

Keywords: track and field; sprinters; sprint start; biomechanics; kinematics; kinetics

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1. Introduction

The sprints are a category of track and field events, usually including 60 m, 100 m, 200 m, and 400 m. According to the technical and rhythmic characteristics of the race, all track and field sprint events are commonly divided into the start, acceleration, and maximum speed phases. As the distances of the races shorten, the sprint start phase becomes even more important for achieving superior performance. In general, world-class 100 m sprinters can achieve around one-third of their maximum velocity in around only 5% of the total race time by the instant they leave the blocks [1]. Thus, this has led to sprint start performance being strongly correlated with overall 100 m time [1]. Given the importance of the sprint start, a wide range of research has emerged in the past 40 years from biomechanics which mainly used high-speed video cameras and force plates [2–5].

A considerable amount of literature has been published on set position, which focuses on foot plate spacings [6–10], foot plate inclination [11,12], and joint angular kinematics [2,13–16]. The existing research recognizes that elongated starts with increased push time do not necessarily produce a greater force to increase start velocity within-group [14], and foot plate inclination has no effect on block power, but the greater the rear block inclination, the greater the horizontal force [12]. However, definitive recommendations on antero-posterior distance and inclination of foot plates are still lacking. In the set position, Mero concluded that there was no significant correlation between the knee, trunk angle, and 100 m performance, but the hip angle of the rear support leg was significantly smaller

in high-level athletes than in medium-level athletes [15]. Nevertheless, a decrease in hip angle may proportionally increase the load on the extensors and thus decrease their contractive force, and therefore a smaller hip angle is not recommended for sprint start [17]. However, there has been little agreement on the correlation between reaction time and 100 m performance. One of the studies showed that there are no significant differences in reaction time among the elite groups [18,19]. It has been observed from another study that the athletes' 100 m performance improved from 9.94 to 9.87 s, and their reaction time also improved accordingly from 0.163 to 0.133 s, indicating that improvement in reaction time is significant for overall performance improvement [20]. Related to sprinter joint angles configuration in the set position, a previous experimental study has shown that a rear knee angle of 90° can generate higher block velocity than rear knee angles of 115° and 135° [21]. In contrast, Ralph Mann believes that elite athletes' rear knee angle of 135° is an optimal angle in the set position, while 130° and 140° both fall into the poorer category [22]. Consequently, it is unclear whether the knee angle of the rear support leg in the set position affects sprint start velocity. In addition to external kinetics, a consensus has been reached according to which the horizontal block impulses are the determining factor of the horizontal velocity at block exit [23–25]. However, the evident important force generated against the blocks could help gain a deeper understanding of block velocity. Fewer comparative studies based on the force–velocity curves during the pushing phase have been carried out in sprinters of different levels, and this will further constrain the targeted training practices.

To reconcile these contradictory findings and to answer the question of the key factors of sprint start, this paper has three objectives. The initial objective is to clarify whether the start block setting varies among different levels of sprinters. The second objective is to demonstrate whether the joint angular kinematics affects sprint start performance. Third, to analyze the forces generated during the pushing phase to identify which specific force affects the start performance. Such detailed comparisons are much better to understand sprint start biomechanics. To this aim, biomechanical descriptors of sprinters of different performance levels during sprint start were tested and analyzed, which can be better to identify the right direction for the practice of sprint training.

2. Materials and Methods

2.1. Participants

Ten high-level and ten medium-level Chinese male sprinters were recruited, and the basic information of the two groups is shown in Table 1. The high-level group inclusion criterion is that the best sprinters' performance is in the range of 10.00–10.99 s, with medium-level group's performance is in the range of 11.00–11.99 s. In this study, sprinters in the high-level group who averaged the best 100 m performance are approximately at the national level (10.51 ± 0.19 s), with four of them being members of the Chinese national team. The high-level group has trains six times per week and their running distance is about 2000–2500 m. Medium-level sprinters are amateurs from university clubs (11.49 ± 0.36 s), and their running distance is about 2200–2800 m per week. Differences between the two groups were confirmed by comparing personal best official 100 m performance. All sprinters were informed about the purpose of the study and its procedures. Written consent was obtained and the athletes, as voluntary participants, could withdraw at any time of the research.

Table 1. Basic information of test subjects ($n = 20$).

	Age (years)	Height (cm)	Weight (kg)	Block Velocity (m/s)	100 m Personal Best (s)
High-level group ($n = 10$)	21.40 ± 1.58	177.86 ± 4.32	69.13 ± 6.95	3.42 ± 0.27	10.51 ± 0.19
Medium-level group ($n = 10$)	20.00 ± 3.06	178.95 ± 3.29	68.86 ± 4.98	3.16 ± 0.23	11.49 ± 0.36

2.2. Measurements

Measurements were conducted at the beginning of late autumn, after the competitive season. This time was selected so as not to interfere with their normal training on the one hand, and on the other hand to put the sprinters in a better competitive state just after the national competition. Standing body height was measured with the head positioned in plane using a stadiometer (SH-V20, Zhengzhou Shanghe Electronic Technology Co., Ltd., Zhengzhou, China) and rounded to the nearest 0.01 cm. Body mass was also recorded with an accuracy of 0.01 kg using a stadiometer (SH-V20, China).

In this study, six high-speed cameras were used for bilateral fixed-point fixed-focus filming of 10 m in the acceleration phase, with a camera height of 1.25 m, a total field of view of 15 m, the main optical axis aligned with the middle of the field and perpendicular to the plane of sprinters movement, and a filming distance of 15 m, with a filming frequency of 350 Hz. Joint kinematics were assessed by Simi-Motion 7.50 capture system (SIMI Reality Motion Systems GmbH, Unterschleißheim, German), with a resolution of 2046×1086 . In this way, the joint angles were recorded. The Kisprint (Kistler Type 9693A, Winterthur, Switzerland) was placed on the athletic track, synchronized with a self-contained starting gun, with a sampling frequency of 1000 Hz. In the Kisprint Fx, the Fy strain force is in the range of $-2.5/2.5$ kN and the Fz is in the range of $-3.5/3.5$ kN. The synchronization signal is triggered by the starting gun (Figure 1). The starting block parameters, reaction time, push time, and kinetics parameters during the push phase were recorded by the Kisprint (Kistler Holding AG (a.k.a. “box”), Winterthur, Switzerland).

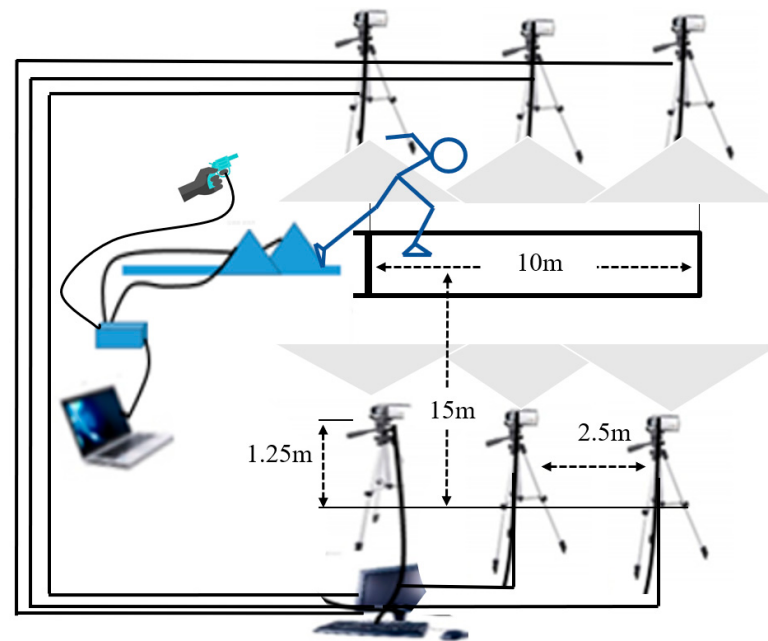


Figure 1. Measurement design of sprint start.

2.3. Procedures

The participants were asked to maintain their normal intake of food and fluids, but to avoid any training activity 48 h and food 3 h before testing. In order to improve the accuracy of image resolution, the athletes were required to wear tight-fitting dark-colored tops and shorts.

Before the test, a 30 min warm-up (jogging, stretching, skipping drills, and short accelerations) was conducted by the athletes. Subsequently, the same experimenter executed tests on specific anatomical points, including the left and right sides of the head (upper ear edge), left and right shoulder joints (acromion), left and right elbow joints (center of ulnar humerus elevation), left and right wrist joints (mid-point of ulnar tuberosity elevation), left and right hip joints (apex of greater trochanter), right and left knee joints (femoral

epicondyle), the lateral aspect of the right and left ankle joints (fibular malleolus), the medial aspect of the right and left ankle joints (lower edge of the tibial malleolus), and the heels and toes. After the reflective points were fixed, a static calibration action was filmed, which was used for the establishment of the 2D mannequin.

Each trial was initiated with the “on your marks” and “set position” commands provided by a qualified starter. When the “on your marks” was issued, the tester started on both the Kisprint and the high-speed camera for the test. After “the gun” signal, the participants left the starting block and ran as fast as possible for at least 10 m. This test requires the sprinters to complete three maximal-effort 10 m block start sprints interspersed with 10 min of rest. Test–retest reliability of the block start position was assessed by interclass correlation coefficients calculated from three consecutive block starts. High reliability was found ($r = 0.96$), which indicated that the applied protocol was uniform across the sprinters.

2.4. Data Analysis

This study analyzed the phase from the starting gun fires until the front block exit. To analyze the efficiency of three different biomechanics conditions, three critical events in the starting block phase (reaction time, push phase, and front leg push) were identified, as seen in Figure 2.

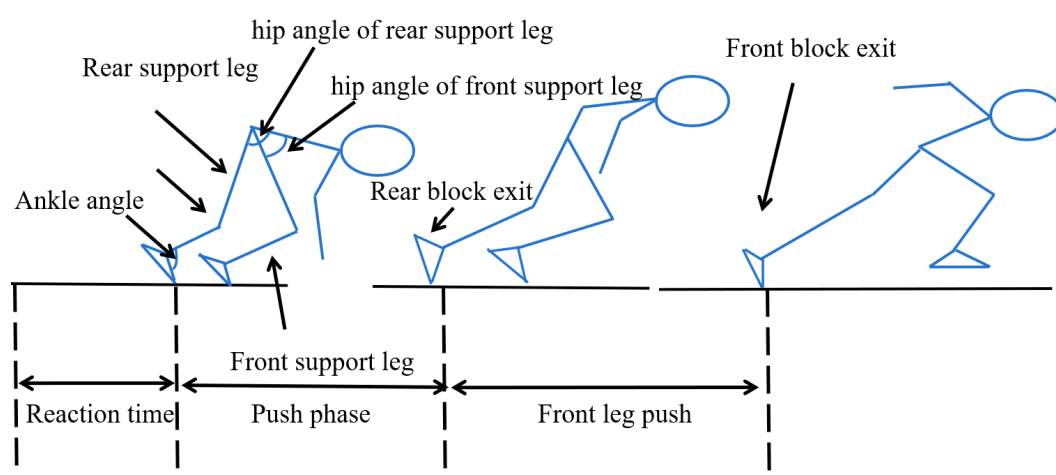


Figure 2. A schematic representation and definition of the events and associated phases during the sprint start.

Firstly, the captured video was imported into Simi Motion 8.5 analysis system to analyze the kinematic data of the athletes, and then two-dimensional joint point coordinates were established by manually punching the points, and finally the joint point coordinates were smoothed by using low-pass digital filtering with a cut-off frequency of 15 Hz. Starting kinetic data were obtained directly from the Kisprint. Descriptive statistics (mean $\pm$ SD) were calculated for all variables. The Shapiro–Wilk test indicated a normal distribution for all variables. Comparisons between high-level and medium-level sprinters were examined by one-way analysis of variance (ANOVA) and the effect size was calculated using η^2 . Effect sizes were interpreted as a small effect at $0.01 \leq \eta^2 < 0.06$ and a medium effect $0.06 \leq \eta^2 < 0.14$ and a large effect $\eta^2 \geq 0.14$. The level of significance was set at $p \leq 0.05$, * indicating that the differences were significant. Data processing was performed with SPSS26.0 (v.26.0, SPSS, Inc. Chicago, IL, USA).

3. Results

3.1. Starting Block

In Figure 3, the average horizontal distance from the front and rear block to the starting line of high-level athletes were not significantly different from that of medium-level athletes

(respectively, 52.15 ± 4.78 cm, 81.00 ± 5.77 cm vs. 52.10 ± 5.99 cm, 82.35 ± 5.83 cm, $p > 0.05$). The average angles of the front and rear blocks of high-level athletes were not significantly different from that of medium-level athletes (respectively, $46.50 \pm 2.42^\circ$, $45.00 \pm 3.33^\circ$ vs. $54.00 \pm 2.11^\circ$, $51.50 \pm 4.74^\circ$, $p > 0.05$).

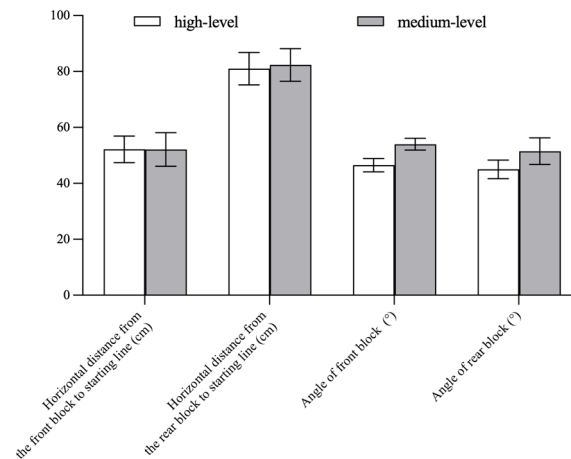


Figure 3. Comparison of the starting block parameters of sprinters at different levels.

3.2. Kinematics

All kinematic results are presented in Figure 4. Only at front block exit is the ankle angle of the swinging leg for high-level sprinters ($104.48 \pm 12.81^\circ$) significantly greater than that of medium-level sprinters ($92.73 \pm 11.92^\circ$) ($p < 0.05$, $F = 4.51$, $\eta^2 = 0.20$, 90% CI = 0.01, 0.424). Similarly, the ankle angle of the front support leg is significantly greater for high-level sprinters ($144.06 \pm 5.75^\circ$) compared to medium-level sprinters ($134.60 \pm 9.55^\circ$) ($p < 0.05$, $F = 7.20$, $\eta^2 = 0.29$, 90% CI = 0.034, 0.497).

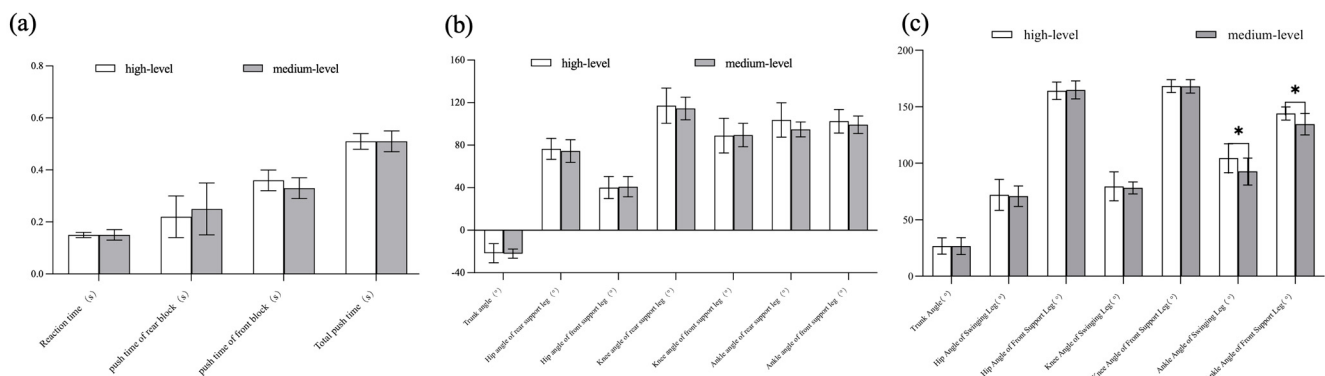


Figure 4. (a) Comparison of the characteristic parameters of the starting time of sprinters at different levels. (b) Comparison of joint angles at set position of sprinters at different levels. (c) Comparison of joint angles at front block exit of sprinters at different levels. * Represents $p < 0.05$.

3.3. Kinetics

All kinetic results are presented in Figure 5 and Table 2. In RFD, the vertical RFD of the rear block of the high-level sprinters was 7.77 ± 3.26 N/s-kg, significantly lower than that of the medium-level sprinters at 13.87 ± 7.08 N/s-kg ($p = 0.02$, $F = 6.12$, $\eta^2 = 0.25$, 90% CI = 0.02, 0.471); the rear block RFD of 15.57 ± 6.09 N/s-kg in high-level sprinters was significantly lower than that of 22.92 ± 8.84 N/s-kg in medium-level sprinters ($p = 0.04$, $F = 4.69$, $\eta^2 = 0.21$, 90% CI = 0.003, 0.43). At maximum starting force, the maximum horizontal force in the front block of high-level 100 m athletes was 1.18 ± 0.09 N/kg, significantly higher than that of medium-level sprinters at 1.03 ± 0.16 N/kg ($p = 0.03$, $F = 4.69$, $\eta^2 = 0.25$, 90% CI = 0.018, 0.465). The maximum vertical force of the rear block of the high-level

100 m athlete was 0.88 ± 0.24 N/kg, significantly lower than the medium-level sprinter's 1.03 ± 0.16 N/kg ($p = 0.05$, $F = 4.42$, $\eta^2 = 0.20$, 90% CI = 0.00, 0.421).

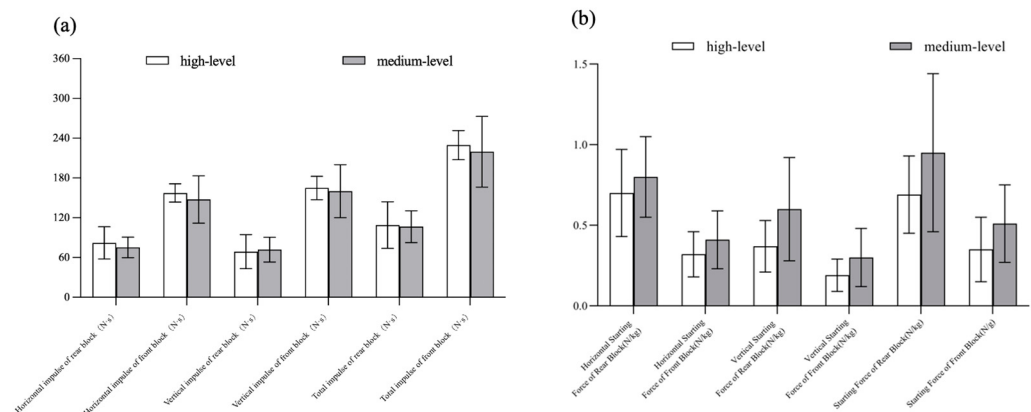


Figure 5. (a) Comparison of starting impulse of sprinters at different levels during push phase. (b) Comparison of starting force of sprinters at different levels during push phase.

Table 2. Comparison of rate of force development and maximum starting force of sprinters at different levels during push phase.

	High-Level	Medium-Level	F	p	η^2
Horizontal RFD of Rear Block (N/s·kg)	15.31 ± 7.46	21.79 ± 10.32	2.59	0.13	0.13
Horizontal RFD of Front Block (N/s·kg)	4.10 ± 0.55	3.90 ± 0.72	0.45	0.51	0.02
Vertical RFD of Rear Block (N/s·kg)	7.77 ± 3.26	13.87 ± 7.08	6.12	0.02 *	0.25
Vertical RFD of Front Block (N/s·kg)	4.53 ± 0.94	4.68 ± 1.35	0.08	0.78	0.00
RFD of Rear Block (N/s·kg)	15.57 ± 6.09	22.92 ± 8.84	4.69	0.04 *	0.21
RFD of Front Block (N/s·kg)	6.03 ± 1.03	6.04 ± 1.46	0.00	0.98	0.00
Maximum Horizontal Force of Rear Block (N/kg)	1.14 ± 0.33	1.30 ± 0.21	1.84	0.19	0.09
Maximum Horizontal Force of Front Block (N/kg)	1.18 ± 0.09	1.03 ± 0.16	5.90	0.03 *	0.25
Maximum Vertical Force of Rear Block (N/kg)	0.88 ± 0.24	1.12 ± 0.26	4.42	0.05 *	0.20
Maximum Vertical Force of Front Block (N/kg)	1.35 ± 0.16	1.24 ± 0.23	1.46	0.24	0.08
Maximum Total Force of Rear Block (N/kg)	1.42 ± 0.38	1.71 ± 0.29	3.59	0.07	0.17
Maximum Combined Force of Front Block (N/kg)	1.78 ± 0.17	1.61 ± 0.27	2.98	0.10	0.14

* Represents significant.

4. Discussion

This study aimed to analyze some kinematic and kinetic variables associated with start block performance that differentiated high-level sprinters from medium-level sprinters. However, no differences between the two groups were found on starting block, reaction time, and push time. In the starting block, both groups of sprinters used the normal style start, suggesting that the normal style may be optimal for sprinter start. Other studies confirmed this finding, showing that the medium style enables the sprinter to be the fastest over the 20-yard and 50-yard sprint [26,27]. Although a previous study has also shown that sprinters using elongated versus shortened and normal styles at the start increased block velocity, excessive time spent on the push phase resulted in lower 5 m and 10 m performance [10]. Moreover, the medium style allows the sprinter to have a good torso posture as well as to have a greater first step length compared to the shortened style [28]. Thus, the normal style may not produce the fastest block velocity, but it is a great advantage for short-distance speeds. It is commonly recognized that the generation of horizontal force is greater with steeper block plates. When examined cross-sectionally across a broad spectrum of sprinters, habitual foot plate inclination has little effect on block velocity [12,29].

The major limitation of the present study is the lack of sprinters' anthropometrics, strength, and flexibility information, which combine to influence the choice of the sprinter in the block start. Further research is necessary to clarify the mechanism underlying the biomechanical influence of morphology and physical fitness on the block start.

The result of this study on the reaction time is consistent with the result of Susanka et al.'s study [30]. Contrary to Xie Hui song's finding, improvement in reaction time is significant for overall performance improvement among sprinters with a 100 m performance from 9.94 to 9.87 s [20]. A possible explanation for this may be that there is no statistically significant causal relationship between reaction time and overall performance. Reaction time mainly depends on several physiological factors, such as arrival of the start signal stimulus at the sensory organ, neural transmissions, and processing, which are largely influenced by genetics. The magnitude of the increase in reaction time by increasing these influences is very weak. In addition, a wide range of sprinters have a reaction time of 0.13–0.17 s, and a slight change will not lead to statistically significant changes in overall performance. In terms of time parameters, push time may not be a key factor in block velocity. The reason for this result is that block velocity is not only determined due to push time, but also depends on kinetic parameters. There is a further problem regarding whether the front or the rear support leg plays a greater role in block velocity. The push time of the front block was 1.64 and 1.32 times longer than that of the rear block in high-level and medium-level sprinters, which demonstrates that the front support leg is more important for block velocity.

At the set position, the joint angle was not a key factor in block velocity in this study. Contrary to earlier findings, however, Mero showed that elite sprinters had a 41° hip angle in the front support leg and an 80° hip angle in the rear support leg, while those of average athletes were of 52° and 80° [15]. However, at the 2018 Indoor Athletics Championships, the winner Coleman had a 86.3° hip angle for the rear support leg and a 57.3° hip angle for the front support leg, and the third place, Baker, had angles of 73.5° and a 46.2°, a result which is clearly at odds with Mero's proposed criteria for elite athletes [31]. The knee angle at the set position has also been controversial in previous studies. Ben Johnson had 104° and 130° knee angles for the front and rear support leg, which did not differ from the other athletes studied by Borzov (front knee angles of 92–105° and rear knee angles of 115–138°) [7,32]. Therefore, it is evident that knee angles in the front and rear support leg at the set position are not key factors influencing block velocity. In contrast to the considerable attention given to hip and knee angles, the influence of ankle angles at the set position on block velocity has received limited attention in previous studies. Bezodis et al. examined the correlation between athletes' front and rear ankle angles for the support leg and force, with correlation coefficients of −0.07 and −0.17, respectively, indirectly supporting our study's results [33]. In general, there are three main reasons that can explain the joint angle of the set position not being a key factor affecting the block velocity: the length of the sprinter's limb proportions, the sprinter's elastic strength, and the sprinter's flexibility [15]; training methods and further research are needed to better understand the underlying biomechanics.

At front block exit, high-level sprinters only show a significantly greater ankle angle for the front support and swinging legs than medium-level sprinters, as shown in Figure 6. Our findings match those observed in an earlier study, indicating that the ankle joint is actively engaged in positive work in the later stages of the push phase [34]. There is a common belief that greater joint angle extension leads to better block velocity; however, this study also indicates that the hip and knee joint of the front support leg are not fully extended at the front block exit. Brazil et al. showed that hip and knee joints begin negatively contributing at the later stages of the push phase [34]. The ankle angle of the swinging leg is significantly larger in high-level sprinters compared to medium-level sprinters at the front block exit. A proficient starting technique involves both feet swiftly pushing the blocks after hearing the gunshot, followed by keeping both feet close to the ground and positively swinging

forward [35]. The increased ankle angle of the swinging leg enables the sprinters to avoid prematurely lifting their center of gravity, favoring the generation of horizontal velocity.

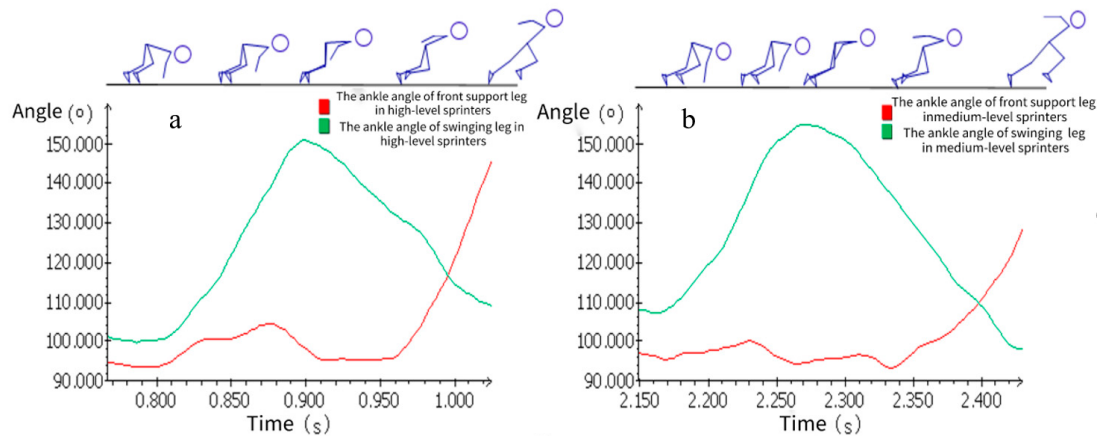


Figure 6. Change in ankle angle of front support leg and swinging leg during the push phase in high-level (a) and medium-level (b) sprinters.

Verhoshansky and Schmidbleicher defined starting force as the ability to achieve the highest force in a short period of time, which was determined as the force value achieved in the first 50 ms [36]. Studying the starting force of sprinters is crucial for researchers and coaches to recognize the impact of starting force on block velocity. The present study demonstrated that the relevant starting force did not differ significantly between different levels of sprinters. The reason for this result is that the shorter duration and smaller force generated during the first 50 ms (20–25% of the total initiation time), do not yet constitute a significant mechanical factor influencing block velocity. According to sports biomechanics principles, completing the initial phase too rapidly may reduce the ability to apply significant force in the subsequent stages, potentially influencing overall block velocity [37]. Regarding rate of force development (RFD), medium-level athletes generate significantly greater vertical RFD in the rear block during the 50–200 ms time period compared to high-level athletes, indicating that medium-level athletes generate more force vertically during this period, which will be detrimental to the horizontal velocity. The higher RFD of the rear block in medium-level sprinters compared to than in high-level sprinters is due to the fact that medium-level sprinters produce a greater vertical RFD and a greater horizontal RFD.

In maximal starting force, high-level sprinters generate a significantly larger maximum horizontal force of the front block compared to the medium-level sprinters. Meanwhile, medium-level sprinters generate a significantly larger maximum vertical force of the rear block compared to the high-level sprinters, as seen in Figure 7. These results are in contrast to the earlier studies according to which rear block force magnitudes are the most predictive external kinetic feature of block power [38]. Proponents of maximum force of the rear block argue for higher forces throughout the entire rear leg push as well as greater pre-tension against the rear block in the set position [39]. In fact, as seen in this study, the medium-level sprinters generate greater maximal horizontal force of rear block than high-level sprinters (1.30 N/Kg vs. 1.14 N/Kg) but this does not result in higher block velocity. According to the results of this study, high-level sprinters had 1.64 times longer front block contact time than rear block contact time, and medium-level sprinters also had 1.32 times longer front block contact time than rear block contact time. Previous research supports the results of this study according to which the front leg contributes 66–76% of the total horizontal impulse due to the 1.9–2.4 times longer block contact time than that contributed by the rear leg, and group mean block velocities are significantly greater with the stronger leg on the front block [40–42].

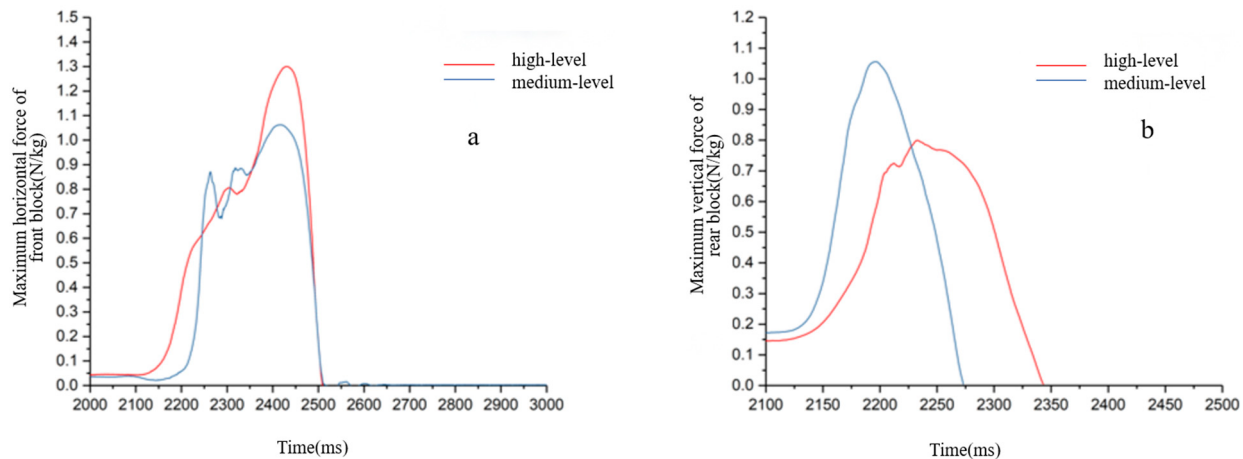


Figure 7. Comparison of the maximum horizontal force of front block (a) and the maximum vertical force of rear block (b) of sprinters at different levels during push phase.

The limitation of this study are the absence of clear joint kinetics, morphology, strength, and flexibility on block velocity, and future research should explore this further. Another limitation is shown by the small sample size, which may not be completely generalizable to the interpretation of block velocity.

5. Conclusions and Suggestion

In conclusion, the results of the present study emphasize that kinematics and kinetics simultaneously influence block velocity. Overall, the start kinematics of high-level sprinters is characterized by a greater ankle angle of the swinging leg and front support leg at the front block exit. In addition, high-level sprinters generate greater maximum horizontal force in the front block and smaller maximum vertical force in the rear block. These findings contribute in several ways to our understanding of sprint start and provide a biomechanical basis for practice training.

From a practical point of view, improving block velocity requires promoting the sprinters' technique and strength in the following ways: (1) Increase ankle plantar flexion flexibility and strength, with exercises such as lying tibialis anterior stretch, holding for 20–30 s, 4–6 sets, twice per week, or resisted plantar flexion with band or straight-knee jumps, 8–12 reps and 4–6 sets; (2) Increase strength in the front support leg, with exercises like 85–90% 1 RM squat, deadlift, 6–8 reps and 4–6 sets, and 8–10% body mass resisted block running. Incorporating both aspects into training practice can better improve starting athletic performance.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available upon request from the corresponding author (Z.L.). The data are not publicly available due to privacy.

Conflicts of Interest: The authors declare no conflicts of interest.

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