On the importance of "front-side mechanics" in athletics sprinting

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ABSTRACT

Practitioners have for many years argued that athletic sprinters should optimise front-side mechanics (leg motions occurring in front of the extended line through the torso) and minimise back-side mechanics. This study aimed to investigate if variables related to front- and back-side mechanics can be distinguished from other previously highlighted kinematic variables (spatiotemporal variables and variables related to segment configuration and velocities at touchdown) in how they statistically predict performance. Twenty-four competitive sprinters (age 23.1 ±3.4 yr, height 1.81 ±0.06 m, body mass 75.7 ±5.6 kg, 100-m personal best 10.86 ±0.22 s) performed two 20-m starts from block and 2-3 flying sprints over 20 m. Kinematics were recorded in 3D using a motion tracking system with 21 cameras at a 250 Hz sampling rate. Several front- and back-side variables, including thigh- (r=0.64) and knee angle (r=0.51) at lift-off, and maximal thigh extension (r=0.66), were largely correlated (p<0.05) with accelerated running performance (ARP), and these variables displayed significantly higher correlations (p<0.05) to ARP than nearly all the other analysed variables. However, the relationship directions for most front- and back-side variables during accelerated running were opposite compared to how the theoretical concept has been described. Horizontal ankle velocity, contact time and step rate displayed significantly higher correlation values to maximal velocity sprinting (MVS) than the other variables (p<0.05), and neither of the included front- and back-side variables were significantly associated with MVS. Overall, the present findings did not support that front-side mechanics were crucial for sprint performance among the investigated sprinters.

Keywords: sprint mechanics, sprinting skills, foot speed, lower-limb kinematics, body configuration

INTRODUCTION

Athletic sprint running performance is regulated by a complex interaction of numerous factors. Many studies have examined the mechanics of linear sprinting, with the majority focusing on spatiotemporal variables. The fastest runners maximize their acceleration and maximum sprinting velocities by applying greater mass-specific ground forces,[1-3] but research literature has so far provided limited information regarding how sprinting athletes should optimize their movements. Due to technology limitations, experimental kinematic studies have typically focused on the measurement area either around the start,[4-6] the acceleration phase [7-10] or during the maximal velocity phase,[11-13] typically assessing 1-3 steps. Only a few scientific studies have investigated the kinematics of athletic sprinting based on high-resolution assessments of >6 steps.[14-16] However, none of these investigations focused on the relationship between body configuration and performance.

Previous kinematic studies have emphasised the importance of body configuration and lower-limb segment velocities at touchdown.[8,10-13,17-19] In contrast, authors of the International Association of Athletics Federations (IAAF) Coaches Education and Certification System's sprint curriculum argue that the elite world of sprinting for more than 20 years has optimized front-side mechanics and minimized back-side mechanics.[20] According to Mann & Murphy,[20] groups of variables related to these concepts can be identified during any portion of the sprint race by simply drawing a straight line through the upper body (trunk). Segments in front of the line are at the 'front-side' while segments behind the line are at the 'back-side'[20] (as illustrated in Figure 2). 'Front-side' and 'back-side' mechanics are expressed in specific joint- and segment angles that relate to these segments at the 'front-side' and 'back-side' (see methods for details). However, this practical concept remains to be scientifically tested. If front-side mechanics were essential for linear sprinting performance, one would expect that the specific variables related to front- and back-side mechanics are associated with sprint performance.

The sparsity of scientific information regarding how sprinters should execute their movements justifies more research in this area. Therefore, based on a full-body kinematic analysis of multiple steps during both the acceleration and maximal sprint velocity phase in well-trained competitive sprinters, the aim of this study was to investigate if variables related to front- and back-side mechanics can be distinguished from other kinematic variables in how they statistically predict performance.

METHODS

Subjects

Twenty-four male Norwegian competitive sprinters (age 23.1 ±3.4 yr, height 1.81 ±0.06 m, body mass 75.7 ±5.6 kg, lean body mass 70.4 ±4.8 kg, fat mass 9.7 ±1.4%, personal best 100-m 10.86 ±0.22 s) voluntarily signed up for this study. The athletes had performed sprint training for 9 ±4 years. All athletes were healthy and free of injuries at the time of testing. The Norwegian Data Protection Authority approved the study. All subjects signed an informed consent form before the experiment and were made aware that they could withdraw from the study at any point without providing an explanation. The study was conducted in accordance with the Declaration of Helsinki.

Design

All experiments were performed in a period of three days during the competition season (middle of August) in an indoor athletic venue. The middle of the straight was used for data collection.

After a self-selected warm-up procedure, the participants performed two 20-m starts from block followed by two or three 20-m flying sprints. Recovery time among trials was self-selected (6-10 min). Kinematics were recorded in 3D using the Qualisys motion tracking system with 21 Oqus cameras (Qualisys AB, Gothenburg, Sweden) at a 250 Hz sample rate. The setup allowed us to analyse nine steps for each subject during the starts (step number 2-10) and six steps for each subject during the flying sprint trials (Figure 1). The actual data recording distance for both conditions was 18 m, limited by the number of cameras. A dual-energy X-ray absorptiometry (DXA) scan was performed on the same day to determine body composition.

*****Figure 1*****

Methodology

Regarding nutrition, hydration, sleep and physical activity, the athletes were instructed to prepare themselves as they would for a regular competition, including no high-intensive training the last two days before testing. The sprint starts followed standardised procedures as outlined by the IAAF.[21] For the flying sprints, each individual was instructed to build up speed over a self-selected in-run distance (typically 30-50 m) before entering the measurement zone with maximal velocity. One athlete had to withdraw from the flying sprints due to a groin strain suffered immediately after the finish line in the second 25-m start.

Camera and reflective marker placements, data recordings, filtering and analyses are previously described in Ettema et al.[16] Centre of mass (CoM) position was calculated according to de Leva.[22] The kinematic variables included in the statistical analyses were categorised as i) front- and back-side variables, ii) variables related to segment angles and lower-limb velocities at touchdown and iii) spatiotemporal variables. This categorisation allowed us to explore whether front- and back-side variables distinguish from other, previously highlighted kinematic variables in how they predict performance. Specific front- and back-side variables included maximal thigh flexion, inter-thigh angle at touchdown, lift-off angle, thigh- and knee angle at lift-off, maximal thigh extension and rear knee flexion angle at maximal thigh extension, based on our interpretation of Mann & Murphy's argumentation.[20] Variables related to segment angles at touchdown (for the stance leg) included trunk-, thigh-, knee-, touchdown- and inter-thigh angles. Variables related to lower-limb segment velocities at touchdown included horizontal ankle velocity (horizontal velocity of the lateral malleolus marker for the soon-to-be stance foot relative to CoM), angular thigh velocity and angular shank velocity. The latter variables were based on mean velocity of the swing foot the last eight samples prior to touchdown. Typical error (TE) (based on within-sprint calculations for six steps during MVS) was <3° for all angular position variables, except for inter-thigh angle at touchdown (5.5°). Coefficient of variation (CV) values were also acceptable for most variables (<6%), except for angular thigh- and shank velocity (10-12%). All angles are illustrated in Figure 2.

*****Figure 2*****

Spatiotemporal variables included step length (SL), step rate (SR), contact time (CT) and aerial time (AT). We defined accelerated sprinting performance as mean step velocity for step 2-10, while maximal velocity sprinting (MVS) was defined as mean step velocity of all the six assessed steps during the flying sprints. TE and CV (based on within-sprint calculations for six steps during MVS) within-sprint for mean step velocity were 0.06 $m \cdot s^{-1}$ and 0.6%, respectively, while corresponding between-sprint values were 0.03 $m \cdot s^{-1}$ and 0.5%, demonstrating excellent repeatability of the criterion measure. CV within sprint at MVS was 2-3% for SL and SR, and 3-4% for CT and AT.

Statistical analyses

Statistical analyses were performed using IBM SPSS Statistics 22.0 (SPSS Inc., Chicago, IL, USA). Mean and standard deviation for all analysed variables are presented. Shapiro Wilks tests revealed that none of the variables deviated statistically from distribution of normality. Pearson's R was used to examine the relationship between sprint performance and the included kinematic variables. These analyses were based on best individual trial. Correlation values were interpreted categorically as trivial, small, moderate, large or very large using the scale presented by Hopkins et al.[23] A paired samples T-test was used to analyse changes in kinematic variables between best and worst trial. A two-tailed Williams T-test was used to test differences between two dependent correlations according to the guidelines by Chen & Popovich.[24] The latter analysis was restricted to the mean values for each sprint phase (i.e., the correlation values in the two columns to the right for each table).

RESULTS

Sprint performance and spatiotemporal parameters

The correlation between 100-m season best result and MVS obtained in this study was 0.78 ($p<0.01$) (Figure 3). Only a trivial difference ($0.03\ m \cdot s^{-1}$, $p<0.01$) in mean velocity was observed between best and worst start trial, and the corresponding difference for flying sprints was small ($0.09\ m \cdot s^{-1}$, $p<0.01$). SL displayed overall large and positive correlations with accelerated running performance. SR displayed moderate and positive correlations with MVS, while CT showed moderate and negative correlations with MVS (Table 1). The correlations between body height and SL and CT during MVS were 0.65 ($p<0.05$) and 0.73 ($p<0.01$), respectively. Mean SR was significantly higher in the best vs. worst flying sprint (4.54 vs. 4.48 Hz; $p=0.001$; small effect), while corresponding mean SL remained practically unchanged (2.25 vs. 2.26 m; $p=0.26$; trivial effect).

*****Figure 3*****
*****Table 1 *****

Front- and back-side mechanics

Figure 4 shows stick diagrams of the group mean at the point of lift-off during accelerated running and MVS. Back-side orientation increased with increasing sprint distance. A visual inspection of individual data revealed that practically all the present sprinters displayed back-side movements (leg motions behind the extended line through the upper body) already after 4-5 steps.

*****Figure 4 *****

Table 2 shows mean values (± SD) of kinematic parameters related to front- and back-side mechanics. Maximal thigh flexion displayed significant negative correlations to mean step velocity (large effect magnitudes) for two steps in the early acceleration phase. Lift-off angle was significantly and negatively correlated to third and fourth mean step speed by large effect magnitudes. Thigh angle at lift-off and maximal thigh extension showed significant positive correlations (moderate to large effect) with mean step velocity for practically all the assessed acceleration-phase steps ($p<0.05$). Knee angle at lift-off revealed moderate to large positive correlations with mean step velocity in the acceleration phase. None of the variables displayed significant changes between best and worst trials for neither acceleration nor MVS.

*****Table 2*****

Configuration and segment velocities at touchdown

Table 3 shows mean values (± SD) of kinematic parameters related to segment configuration and velocities at touchdown. Horizontal ankle velocity displayed significant positive correlations with mean step velocity from the fifth step of the assessed acceleration phase (moderate to large effect) and with MVS (moderate effect). None of the other analysed variables displayed a clear relationship with performance, and none of the variables displayed significant changes between best and worst trials for neither acceleration nor MVS.

*****Table 3*****

Differences across dependent correlations

A two-tailed Williams T-test revealed no differences among SL, thigh angle at lift-off, knee angle at lift-off and maximal thigh extension, but these variables displayed significantly higher correlations to accelerated running performance than all other variables ($p<0.05$), except for knee angle at lift-off vs. knee flexion at MTE and horizontal ankle velocity. Horizontal ankle velocity and knee flexion at MTE displayed significantly higher correlations to accelerated running performance than SR, CT, AT, inter-thigh angle at touchdown, lift-off angle, angular thigh velocity at touchdown and trunk-, thigh- and knee angle at touchdown ($p<0.05$), except for knee angle at MTE vs. lift-off angle. Horizontal ankle velocity, CT and SR displayed significantly higher correlations to MVS than all other variables ($p<0.05$).

DISCUSSION

The results from this study showed that front- and back-side variables such as thigh- and knee extension at lift-off, maximal thigh extension and knee flexion at maximal thigh extension (in addition to SL) displayed significantly higher correlations to accelerated running performance than most of the other analysed variables. However, the relationship directions for the majority of these front- and back-side variables were opposite compared to how the theoretical concept has been described by Mann & Murphy.[20] That is, there was a trend towards more back-side movements with increasing performance level. Horizontal ankle velocity, CT and SR displayed significantly higher correlation values to MVS than the other variables, and none of the included front- and back-side variables were significantly associated with MVS.

Mann & Murphy[20] advocate that sprinters should be front-side oriented from the very first step. In this study, back-side movements were observed in all athletes from the fourth or fifth step, and the magnitude of such movements increased gradually thereafter. A similar trend can be seen within a comparable group of sprinters (100-m personal best 10.71 ±0.33 s) in Nagahara et al.[14] by drawing an extended line through the upper body in their corresponding stick figures just prior to lift-off. It is therefore reasonable to argue that the present data are representative for most well-trained sprinters at the same performance level.

The front-side mechanics concept has been argued for using dynamics, as Mann & Murphy[20] state that the force generated during the very last part of ground contact part is minimal, so if sprinters end this "unproductive" portion of ground contact early, they can get back to the "productive" front-side of the movements sooner. However, at the end of push off, force is, 'by law', bound to be low and will in the end reach zero at take-off independent of running technique. Thus, ending ground contact earlier will only serve to shift the "unproductive" portion earlier as well, with the pattern of force remaining largely unchanged. The same authors argue that the best sprinters tend to minimise upper and lower leg extension at lift-off during MVS. In the current study, none of the analysed front- and back-side variables were associated with MVS. The overall large and positive correlation values for knee- and thigh angle at lift-off indicate that an optimal extension in these joints during the acceleration phase is important. Thus, the present findings do not support the notion that back-side mechanics should be minimised, at least in this group of sprinters. Bezodis et al.[5,6] assessed the first step out of the blocks in well-trained sprinters and observed that greater hip extension was associated with higher levels of external power production. Optimal extension in the stance hip joint at lift-off during acceleration is likely important for at least two reasons: i) to ensure maximal utilisation of the hamstrings and glutes and ii) to orient the ground reaction forces more horizontally, particularly when combined with a simultaneous and sufficient knee lift for the swing leg. The swing leg's contribution to propel CoM forward by generating higher ground reaction forces through the stance leg is a mechanism that has been overlooked in most sprint literature. This offers the swing leg movement an extra function, similar to e.g. arm movement in jumping.

The sprinters in this study displayed minimal differences between thigh angle at lift-off and maximal thigh extension, both during acceleration (~1°) and MVS (~ 2°) (Table 2). Moreover, there was a moderate and negative relationship between knee flexion at the point of maximal thigh extension and acceleration performance, indicating that so-called lower-leg back-lift should be minimised. Overall, the findings indicate that sprinters should get back to the front-side as soon as possible after lift-off, without compromising lower-limb extension during ground contact. Based on these considerations, the theoretical underpinning of the concept would be strengthened if the definition of back-side mechanics was reworded to "minimise further backward movements in the lower-limbs after lift-off" or something equivalent.

Hypothetically, it could be argued that excessive lower-limb extension during accelerated sprinting explains the present athletes' lower performance level compared to world-class sprinters. If this is the case, these performance-related variables should not exhibit a consistent linear relationship across levels of performance, but rather change direction at some point. Mann & Murphy[20] argue that if a sprinter fails to achieve front-side dominance from the very beginning of the race, the athlete will be unable to shift from that point forward. That is, if back-side mechanics are dominant from the start, then the sprinter will also finish the race with back-side dominance. The present study design does not allow a verification of this hypothesis.

Several authors have emphasised the importance of body configuration at the point of touchdown, specifically in terms of small touchdown distance[9,10,12,17,19,20] and small knee separation[11,13] during MVS, in addition to forward lean of the body during accelerated sprinting.[10,18] Mann & Murphy[20] expressed the two first variables in absolute horizontal distance, but we chose an angular expression to avoid the possible influence of varying dimensions among athletes. Overall, our results did not reveal an association between sprint performance and any of the analysed variables related to configuration at touchdown (Table 3). Hunter et al.[9] observed that a shortening of the touchdown distance at the 16-m mark could reduce braking forces, while Bezodis et al.[19] reported that a reduced touchdown distance for the first step out of the blocks could lead to enhanced horizontal power production, although there was a limit to the associated performance benefit. It is important to keep in mind that a maximisation of forward propulsion requires an optimal, not maximal, effectiveness of force application. A certain minimum of braking force is required to maintain a stable body posture[10] and this optimal force application is, among other things, related to touchdown distance and forward lean of the upper body. Based on present and previous findings, it appears that between-athlete differences are present for variables related to configuration at touchdown among heterogeneous athlete samples, but not among homogeneous sprinters of higher performance standards. Notably, the 1.7° standard deviation for touchdown angle at MVS (Table 3) among the present athletes was very low, indicating that these sprinters were technically proficient.

A few previous studies have investigated the relationship between performance and variables related to lower-limb segment velocities either immediately prior to[9,12] or during[12,17] ground contact. Hunter et al.[9] observed a significant relationship between an active touchdown (i.e., low horizontal ankle velocity relative to the ground immediately prior to touchdown) at the 16-m mark and magnitude of braking forces, but did not relate this variable to sprint performance. Inevitably, horizontal ankle velocity relative to CoM during support must be equal to forward velocity (performance). Therefore, it would be reasonable to expect a significant relationship between sprint performance and lower-limb segment velocities immediately prior to touchdown as well. We observed significant correlations (mainly moderate effect magnitudes) between horizontal ankle velocity relative to CoM and mean step speed both during accelerated sprinting (moderate to large effect magnitudes) and at MVS (moderate effect magnitudes) (Table 3). Together with SR and CT, horizontal ankle velocity had a greater correlation with MVS than all other variables. In contrast, angular thigh and shank velocity immediately prior to touchdown displayed only trivial or small correlation values with performance. We ascribe these inconsistencies to varying levels of repeatability among variables, as the CV values for angular thigh and shank velocity were approximately double those for horizontal ankle velocity. However, the moderate correlation values (shared variance < 20%) observed for horizontal ankle velocity indicate that other factors are important as well.

The athletes in this study increased their between-trial MVS performance by means of SR. Previous studies have revealed contradicting findings in this area. Otsuka et al.[25] observed that the enhanced MVS from practice (where speed training was performed at perceived maximal intensity) to competition was by means of higher SR. Hunter et al.[7] observed significantly higher SR at the 16-m mark during the best trial. According to anecdotal observations by Mann & Murphy[20] and Haugen et al.,[26] SL remains very stable over time in world-class sprinters, and individual performance changes across competitions or between training and competition are mainly regulated by SR. Salo et al.[27] observed a large variation of performance patterns among elite athletes and concluded that SR or SL reliance is highly individual. However, it should be noted that outdoor assessments of sprinters in previous studies might have been affected by varying wind conditions. Many practitioners would argue that SR is more sensitive to wind speed variations than SL, although this has not been scientifically tested.

CT reduced gradually from 0.195 ±0.017 s in the first complete ground contact period to approximately half the value at the time of peak velocity (0.096 ±0.008 s), while corresponding aerial time increased from 0.049 ±0.018 to 0.124 ±0.06 s (Table 1). These values are similar to previous investigations of well-trained sprinters.[3,15] The lack of a significant relationship between CT and acceleration performance is in contrast to the findings by Coh et al.,[28] while the moderate correlation between CT and MVS performance is in line with previous studies.[28,29] Divergences can be related to sample homogeneity and the fact that taller athletes at the same performance level typically have longer steps and longer contact times.[30] Also, in the present study, CT had a significant relationship to body height.

This is the first study to perform a full-body kinematic analysis of multiple steps in competitive sprinters during both acceleration and MVS. The very large correlation between 100-m season best and MVS test performance indicates that the present experimental setting was valid and appropriately reflected the participants' sprinting performance. However, some study limitations still need to be addressed. Firstly, an acceptable "value" for one kinematic variable may be essential but not necessarily sufficient in itself to ensure a good performance. Moreover, we cannot draw any conclusions about cause-effect relationship between the presented kinematic variables and performance, although some of the relationships can be explained by mechanics. Finally, the relatively homogeneous sample of athletes and the small performance differences observed among trials in the present study may have reduced the possibility of establishing associations with kinematic variables.

CONCLUSION

Front-side mechanics did not predict maximal linear sprinting performance in the present group of sprinters. Even though several front- and back-side variables were largely associated with accelerated running performance, their relationship directions were opposite compared to how the theoretical concept has been described. Instead, the current results emphasise the importance of optimal knee- and hip extension at the point of lift-off.

PRACTICAL APPLICATIONS

The present results do not support the importance of the concept of front-side mechanics for sprint running performance. Thus, this concept should not be regarded as generally applicable. However, the lack of available methodological information related to kinematic assessments of world-class performers precludes comparisons to other athlete samples. At this stage, we cannot generalize our findings to higher-level athletes, and it may well be that world-class athletes provide superior front-side mechanics compared to the present homogeneous athlete sample on a lower performance level. Future studies should therefore aim to assess high-resolution, kinematic data of multiple steps in world-class sprinters and compare sprinters of different performance levels.

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Table 1. Mean values (± SD) of the main sprint performance (step velocity) and spatiotemporal parameters

Step number	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**2-10**	**MVS**
Mean step velocity (s)	4.64	5.63	6.03	6.74	7.34	7.85	7.96	8.40	8.70	7.03	10.18
± SD	0.29	0.32	0.32	0.33	0.33	0.34	0.26	0.37	0.39	1.34	0.25
% of MVS	45.6	55.3	59.2	66.2	72.1	77.1	78.4	82.5	85.5	69.1	100
Step length (m)	1.13	1.31	1.43	1.55	1.64	1.74	1.80	1.89	1.92	1.61	2.25
± SD	0.09	0.07	0.10	0.08	0.11	0.10	0.12	0.10	0.11	0.27	0.08
R	0.22	0.24	0.25	0.64**	0.37	0.41	0.37	0.40	0.48*	0.60*	0.14
Step rate (Hz)	4.11	4.29	4.21	4.34	4.47	4.51	4.42	4.44	4.53	4.36	**4.54**
± SD	0.39	0.30	0.32	0.19	0.29	0.25	0.29	0.24	0.24	0.31	0.18
R	-0.08	-0.17	0.14	-0.65**	-0.45*	-0.01	0.03	-0.35	-0.54*	-0.16	0.48*
Contact time (s)	0.195	0.177	0.164	0.147	0.136	0.132	0.130	0.122	0.116	0.147	0.096
± SD	0.017	0.014	0.011	0.012	0.009	0.010	0.009	0.009	0.008	0.028	0.008
R	-0.29	-0.39	0.11	-0.52*	-0.32	-0.28	0.02	-0.54*	-0.39	-0.05	-0.46*
Aerial time (s)	0.049	0.056	0.073	0.083	0.088	0.089	0.096	0.103	0.105	0.083	0.124
± SD	0.018	0.013	0.019	0.012	0.013	0.012	0.015	0.011	0.010	0.023	0.006
R	-0.08	-0.17	0.14	-0.45*	-0.45*	-0.01	0.03	-0.35	-0.54*	-0.16	-0.11

MVS = maximal velocity sprinting (mean of six steps in the best 20-m flying sprint). R = Pearson's correlation coefficient between kinematic variable and corresponding mean step velocity. * and ** denote significant correlations at $p < 0.05$ and $p < 0.01$, respectively. Bold number denotes significantly higher value in best vs. worst trial ($p < 0.05$).

Table 2. Mean values (± SD) of kinematic parameters related to front- and back-side mechanics

Step number	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**2-10**	**MVS**
Maximal thigh flexion (°)	33.5	30.6	30.5	28.6	26.4	23.6	24.1	21.9	23.4	26.9	20.1
± SD	5.7	5.5	5.3	4.4	5.9	4.0	6.5	4.7	4.1	4.1	3.9
R	-0.08	-0.60*	0.14	-0.57*	-0.02	-0.38	-0.39	-0.36	-0.20	-0.36	0.01
Inter-thigh angle at TD (°)	-50.8	-51.1	-50.8	-44.0	-37.9	-37.7	-38.9	-34.6	-29.8	-40.4	-15.8
± SD	11.6	13.6	10.5	12.8	8.1	10.4	10.2	11.6	10.6	7.9	7.2
R	0.06	0.22	-0.22	0.26	0.08	0.15	0.08	0.41	0.43*	-0.06	0.06
LO angle (°)	40.6	41.8	43.6	45.5	46.7	47.3	48.3	49.5	51.0	46.0	56.7
± SD	2.2	2.2	2.8	2.0	2.1	2.3	2.4	2.4	2.0	1.9	1.9
R	-0.35	-0.62*	-0.57*	-0.26	-0.39	-0.17	-0.36	0.18	-0.06	-0.29	0.10
Thigh angle at LO (°)	124.9	122.9	122.9	121.6	121.3	120.7	120.0	119.9	119.2	121.5	115.4
± SD	5.2	4.1	5.0	4.0	4.9	4.0	4.5	3.7	4.3	3.8	4.1
R	0.32	0.42*	0.56*	0.39	0.70**	0.47*	0.48*	0.43*	0.55*	0.64**	-0.04
Knee angle at LO (°)	154.4	152.2	154.2	154.8	155.1	154.2	153.6	155.4	156.0	154.4	155.4
± SD	7.2	6.4	7.2	6.8	6.3	5.1	4.9	5.5	5.5	5.0	5.3
R	0.37	0.34	0.26	0.40	0.62*	0.36	0.29	0.32	0.55*	0.51*	-0.16
Maximal thigh extension (°)	126.5	123.4	123.1	121.8	121.4	121.1	120.5	120.4	119.7	122.0	117.9
± SD	4.9	4.2	5.1	3.9	4.9	3.8	4.5	3.8	4.4	3.9	3.4
R	0.37	0.49*	0.58*	0.46*	0.70**	0.48*	0.44*	0.50*	0.48*	0.66**	0.08
Knee flexion at MTE (°)	71.8	60.5	62.3	61.4	56.3	51.5	49.0	47.8	46.2	55.1	38.3
± SD	7.6	10.8	6.7	9.6	9.0	8.8	6.1	9.2	6.2	5.7	5.0
R	0.03	0.07	-0.01	-0.39	-0.34	-0.39	-0.26	-0.34	-0.12	-0.40	-0.11

TD = touchdown. LO = lift-off. MTE = maximal thigh extension. MVS = maximal velocity sprinting (mean of six steps in the best 20-m flying sprint). R = Pearson's correlation coefficient between kinematic variable and corresponding mean step velocity. * and ** denote significant correlations at $p < 0.05$ and $p < 0.01$. respectively.

Table 3. Mean values (± SD) of kinematic parameters related to segment configuration and velocities at touchdown

Step number	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**2-10**	**MVS**
Touchdown angle (°)	76.5	85.5	92.5	93.8	94.8	97.1	100.2	99.8	100.0	93.4	105.2
± SD	2.8	4.1	2.9	4.3	2.4	2.6	2.8	2.3	2.6	1.7	1.7
R	-0.36	-0.43*	-0.20	-0.39	-0.39	-0.19	-0.18	-0.37	-0.38	-0.32	-0.09
Trunk angle (°)	36.0	44.8	48.9	51.4	55.1	58.3	62.0	64.4	67.5	54.3	84.2
± SD	6.9	6.4	7.5	6.7	6.4	5.8	5.2	4.6	4.7	5.3	2.5
R	-0.27	-0.06	-0.10	0.33	-0.35	0.19	0.18	0.17	0.28	0.03	0.12
Thigh angle (°)	62.5	55.4	53.9	55.8	57.5	55.4	54.6	55.7	57.4	56.5	60.7
± SD	4.2	5.3	4.2	4.8	3.3	3.7	3.4	3.8	4.5	3.0	3.3
R	0.07	0.10	-0.28	0.45*	0.07	0.30	-0.11	0.33	0.37	0.13	0.04
Knee angle (°)	105.8	108.8	117.9	124.2	129.2	130.4	133.4	135.8	138.6	124.9	153.3
± SD	5.4	6.4	5.0	5.7	4.7	5.2	4.6	5.5	5.5	4.1	4.7
R	-0.28	-0.21	-0.25	0.05	-0.07	0.10	-0.24	0.16	0.18	0.07	0.07
Hor. ankle velocity ($m \cdot s^{-1}$)	1.74	3.03	3.28	3.73	4.38	4.63	4.77	5.06	5.49	4.01	6.49
± SD	0.79	1.13	1.18	1.43	1.02	0.98	1.04	1.10	0.89	0.79	0.49
R	0.14	0.35	0.38	0.51*	0.43*	0.48*	0.42*	0.51*	0.59*	0.43*	0.44*
Angular thigh velocity ($° \cdot s^{-1}$)	337	414	424	415	414	390	397	398	399	399	379
± SD	79	83	87	76	84	87	86	83	91	68	86
R	-0.17	0.35	-0.32	0.30	-0.16	0.07	-0.17	0.02	-0.23	0.10	0.00
Angular shank velocity ($° \cdot s^{-1}$)	45	-128	-137	-163	-241	-267	-290	-298	-338	-202	-445
± SD	132	152	174	160	112	117	121	128	104	91	92
R	-0.08	-0.31	0.15	-0.36	-0.37	-0.23	-0.28	-0.29	-0.40	-0.34	-0.29

MVS = maximal velocity sprinting (mean of six steps in the best 20-m flying sprint). R = Pearson's correlation coefficient between kinematic variable and corresponding mean step velocity. * denotes significant correlations at $p < 0.05$.

FIGURE LEGENDS

Figure 1. Illustration of the experimental setup. A total of 21 cameras were placed alternately on either side ~5 m from the middle of the straight and ~2.5 m above ground level (angled downward).

Figure 2. Definition of angles. The black dot represents centre of mass (CoM). θ_{trunk}. trunk angle relative to horizontal; θ_{thigh}. thigh angle relative to horizontal, where an angle of zero corresponds to the thigh being in alignment with the dotted horizontal line; θ_{knee}. knee angle, where 180° corresponds to fully extended knee; $\theta_{i\text{-}t\text{high}}$. inter-thigh angle, where the sign is negative if the swing thigh is behind stand thigh; $\dot{\theta}_{\text{thigh}}$. angular thigh velocity; $\dot{\theta}_{\text{shank}}$. angular shank velocity; $V_{h\ \text{ankle}}$. horizontal ankle velocity (horizontal component of the velocity difference between the ankle and CoM); θ_{TD} and θ_{LO}. touchdown and lift-off angle, respectively (i.e., the angle relative to vertical between CoM and metatarsal marker).

Figure 3. Relationship between 100-m season best result and maximal velocity sprinting (MVS) obtained in the study.

Figure 4. Stick diagrams of the group mean (thick solid lines) at the point of lift-off in the 1st step (A). 5th step (B). 9th step (C) and at maximal velocity sprinting (D). Extended lines (thin and dotted) through the upper body are added to visualise the degree of front- and backside mechanics.

Figure 1.

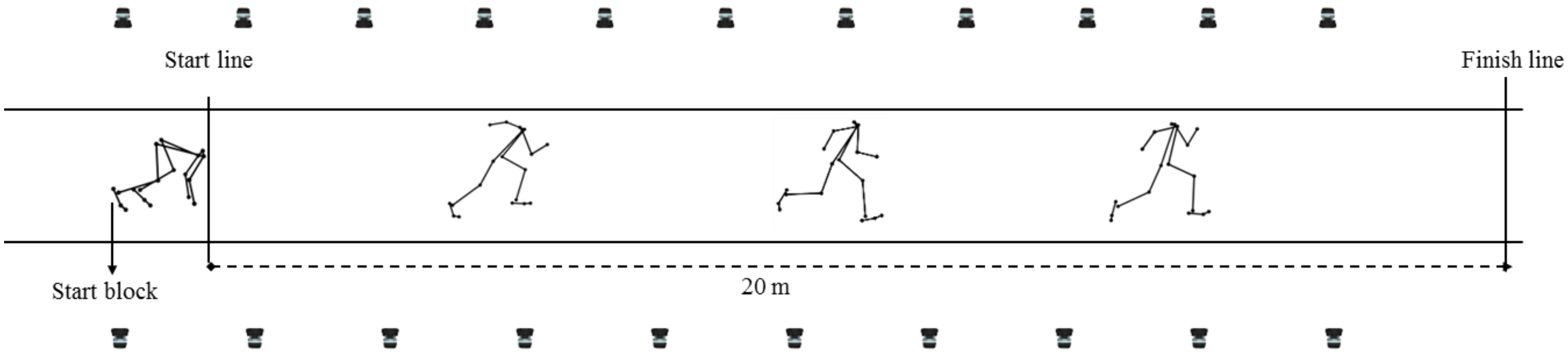

Figure 2.

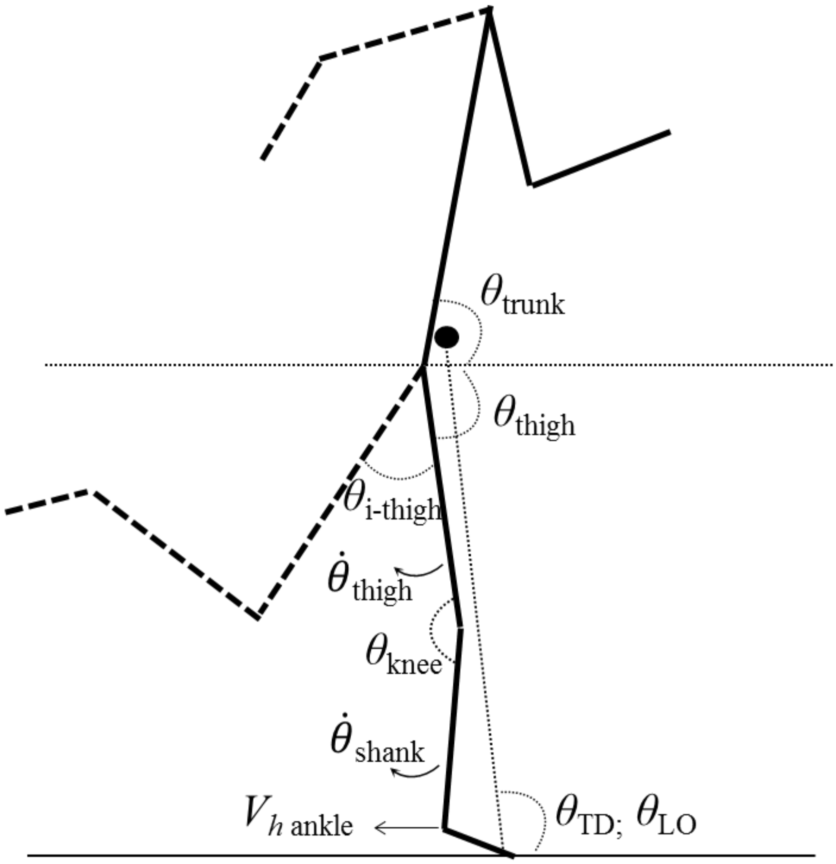
θ_{trunk}
θ_{thigh}
$\theta_{i\text{-}thigh}$
$\dot{\theta}_{thigh}$
θ_{knee}
$\dot{\theta}_{shank}$
$V_{h\ ankle}$
$\theta_{TD};\ \theta_{LO}$

Figure 3.

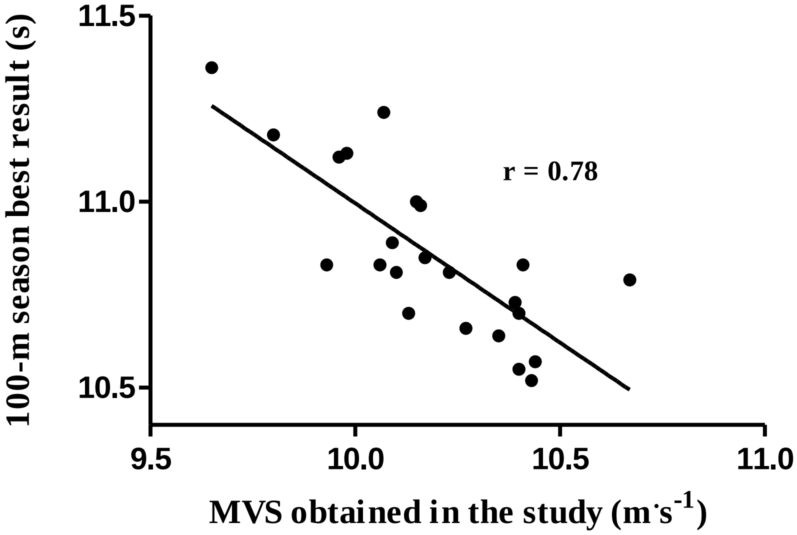
11.5
11.0
10.5
100-m season best result (s)
r = 0.78
9.5
10.0
10.5
11.0
MVS obtained in the study (m·s-1)

Figure 4.