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Relationships between lower limb kinematics and block phase performance in a cross-section of sprinters

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Abstract:

This study investigated lower limb kinematics to explain the techniques used to achieve high levels of sprint start performance. A cross-sectional design was used to examine relationships between specific technique variables and horizontal external power production during the block phase. Video data were collected (200 Hz) at the training sessions of 16 sprinters who ranged in 100 m personal best times from 9.98 to 11.6 s. Each sprinter performed three 30 m sprints and reliable (all ICC(2,3) ≥ 0.89) lower limb kinematic data were obtained through manual digitising. The front leg joints extended in a proximal-to-distal pattern for 15 sprinters and a moderate positive relationship existed between peak front hip angular velocity and block power (*r* = 0.49, 90% confidence limits = 0.08 to 0.76). In the rear leg, there was a high positive relationship between relative push duration and block power (*r* = 0.53, 90% confidence limits = 0.13 to 0.78). The rear hip appeared to be important; rear hip angle at block exit was highly related to block power (*r* = 0.60, 90% confidence limits = 0.23 to 0.82) and there were moderate positive relationships with block power for its range of motion and peak angular velocity (both *r* = 0.49, 90% confidence limits = 0.08 to 0.76). As increased block power production was not associated with any negative aspects of technique in the subsequent stance phase, sprinters should be encouraged to maximise extension at both hips during the block phase.

Keywords: acceleration, biomechanics, coaching, performance, training.

Introduction

In athletic sprinting, the block phase has been subject to numerous descriptive and experimental biomechanical studies. Much of this research has focussed on ‘set’ position technique and considerable inter-participant variation and weak relationships between self-selected ‘set’ position kinematics and sprint start performance have ultimately been reported (e.g. Atwater, 1982; Mero, 1988; Mero, Luhtanen, & Komi, 1983). Once a sprinter reacts to the starter’s gun, they start to generate forces against the blocks and move out of the ‘set’ position. These external kinetics during the block phase have been well documented (e.g. Baumann, 1976; Lemaire & Robertson, 1990; Mero, 1988; Payne & Blader, 1971; van Coppenolle, Delecluse, Goris, Bohets, & Vanden Eynde, 1989) and the higher block exit velocities of better starters have been partly attributed to an increase in force generation with the rear leg (Lemaire & Robertson, 1990; Payne & Blader, 1971; van Coppenolle et al., 1989). However, despite the existence of a large body of information regarding ‘set’ position joint angles and the linear kinematics of the centre of mass (CM) during block exit, there has been limited quantitative assessment of the specific joint kinematics involved in the generation of these forces and thus CM motion (Slawinski et al., 2010b, 2013).

Slawinski et al. (2010b) described the average angular velocities and segmental kinetic energies of a group of eight sprinters, whilst Slawinski et al. (2013) determined the effects of experimental manipulations to ‘set’ position on the joint angular velocities exhibited during block exit. Although it was not the main aim of their study, closer inspection of the variation in the joint angular velocities presented by Slawinski et al. (2010b) indicated that there were considerable differences in the techniques used by the studied group of sprinters even when their overall level of block phase performance was reasonably homogenous (100 m personal best (PB) of 10.30, s = 0.14 s). Investigating whether these variations in technique are related to performance levels across a group of sprinters would be useful to identify how higher levels of block phase performance are typically achieved. The aim of the current study was therefore to identify the key characteristics of the lower limb kinematic patterns during the block phase in a cross-section of sprinters including world-class athletes and to determine the specific aspects of sprint start technique which are associated with higher levels of performance. Since it must be considered that the block phase is not a ‘stand-alone’ part of a sprint, and that striving to maximise block phase performance could potentially affect technique and performance during the subsequent phases, relationships between block phase performance and kinematics at the first touchdown on the track were also assessed.

Methods

Participants

Following study approval from the Local Research Ethics Committee, 16 male sprinters with a mean age of 21, *s* = 5 years, height of 1.78, *s* = 0.05 m, and mass of 74.4, *s* = 8.3 kg provided written informed consent to participate in this study. Their ability levels ranged from world-class (100 m PB of 9.98 s) to university-level (hand timed 100 m PB of 11.6 s); the group mean 100 m PB was 10.95, *s* = 0.51 s.

Protocol

All data were collected at coach-prescribed training sessions. For 13 of the sprinters, data were collected indoors just prior to the competition phase of the indoor season. For the remaining three sprinters, data were collected outdoors during the early competition phase of the outdoor season. Each sprinter completed three maximal effort sprints to 30 m from starting blocks. Sprinters were allowed their usual recovery between sprints, which was typically 8-10 minutes. At all sessions, a single high-speed digital video camera (Motion Pro$^{®}$, HS-1, Redlake, USA; 200 Hz, 1280 × 1024 pixel resolution) recorded movements within a calibrated field of view 2.5 m (indoors) or 4.0 m (outdoors) wide. Due to issues with the camera set-up at one session, rear foot data from one sprinter in the ‘set’ position were unavailable and this sprinter was removed from the analysis when variables reliant upon rear foot data from the early block phase were required.

Data processing

All video clips were imported into digitising software (Peak Motus®, v.8.5, Vicon®, UK) and eighteen points (vertex, seventh cervical vertebra, shoulder, elbow, wrist, third metacarpal, hip, knee, ankle and second metatarsal-phalangeal (MTP) joint centres) were manually digitised from one frame prior to the visually identified movement onset until 10 frames after first stance touchdown. The digitised points were projectively scaled to yield raw sagittal plane displacement data. All subsequent data analysis utilised custom routines developed in Matlab™ (v. 7.4.0, The MathWorks™, USA). Following backward replication of the first frame 10 times to alleviate potential endpoint errors, the data were smoothed using a fourth-order Butterworth digital filter with cut-off frequencies determined individually for each displacement time-history (16 to 28 Hz) via residual analysis (Winter, 2005). Anatomical joint angles were calculated and joint angular velocities throughout the data set were derived using second central difference calculations (Miller & Nelson, 1973). Specific events ('set' position, movement onset, rear foot off blocks, block exit, first stance touchdown) were identified visually from the video clips. The push phase was defined as the time elapsing between movement onset and block exit, and the duration of the rear foot push was also determined. Joint angles at each event and the peak lower limb joint angular velocities during each leg's respective push phase were extracted for each trial.

Whole body CM location was determined (Winter, 2005) using segmental inertia data from de Leva (1996). Inertia data for the feet were taken from Winter (2005) and the measured mass of the spiked shoes was incorporated. Horizontal CM displacement was also calculated from the unfiltered displacement data for use in determining horizontal CM velocity at block exit using first flight phase data (Salo & Scarborough, 2006). The change in kinetic energy during the push phase was then calculated from these velocity data. Using the kinetic energy data and the push phase duration, average horizontal external block power (hereafter termed block power) was calculated as an objective measure of block phase performance since it takes into account both the velocity at the end of the block phase and the time taken to achieve this velocity (Bezodis, Salo, & Trewartha 2010). Block power and all linear displacements were normalised to account for body size according to the convention of Hof (1996) with an adjusted power normalisation (Bezodis et al., 2010).

Statistical analysis

For all variables of interest, mean values for each sprinter were calculated from their three trials. The reliability of these data was quantified using an intraclass correlation coefficient. Model 2,3 was used to include both systematic and random error, and to account for the mean of the three trials being used in the subsequent analysis (Vincent & Weir, 2012). Ensemble group mean and standard deviation data were determined from the individual mean data. For all variables of interest, the mean data from each of the sprinters (i.e. 16 data points) were checked for normality using a Shapiro-Wilk test. The peak front ankle angular velocity was found to be non-normally distributed ($P < 0.05$). Pearson's product moment correlation coefficients (r) between specific technique variables and performance were quantified using the 16 mean values obtained from each individual's three trials. Relationships involving the peak front ankle angular velocity data were quantified using a Spearman's rank correlation coefficient (ρ). Uncertainty in the observed relationships was quantified with 90% confidence limits determined using the Fisher z transformation (Fisher, 1921). If these confidence limits overlapped both substantial positive and negative values (i.e. $r = \pm 0.1$ based on the smallest clinically important correlation coefficient; Cohen, 1988; Hopkins, 2014), the magnitude was deemed unclear. Based on 16 participants, correlations >0.35 or <-0.35 were considered clear and their strength was defined using the convention recommended by Cohen (1988) and Hopkins (2014): moderate (0.3 - 0.5), high (0.5 - 0.7), very high (0.7 - 0.9) or practically perfect (0.9 - 1.0).

Results

All intraclass correlation coefficients equalled or exceeded 0.89 (Tables 1 and 2). The mean push phase duration was 0.358, *s* = 0.022 s (ICC (2,3) = 0.97), and the rear leg pushed against the rear block for 53, *s* = 5% (ICC (2,3) = 0.97) of this total push duration. During the push phase, the sprinters generated a mean block power of 1171, *s* = 268 W (ICC (2,3) = 0.98; normalised mean = 0.53, *s* = 0.08, ICC (2,3) = 0.97). Across all 16 sprinters, a very high, negative relationship (*r* = -0.72, 90% confidence limits = -0.88 to -0.42) existed between 100 m PB time and normalised block power.

The relationships between lower limb joint and trunk angles in the 'set' position and normalised block power were all unclear (all -0.17 < *r* < 0.16; Table 1). All 16 sprinters exhibited a rear leg sequencing in peak joint velocities of knee then hip, followed by ankle (Figure 1a-c). At the front leg, all sprinters with the exception of one exhibited a proximal-to-distal sequencing from hip to knee to ankle (Figure 1d-f). Relationships between peak joint extension angular velocities and normalised block power were unclear for both knees and ankles (Figures 1a, 1b, 1d, 1e). There were moderate relationships between normalised block power and peak angular velocity at both hips (*r* = 0.49; 90% confidence limits = 0.08 to 0.76; Figures 1c and 1f). Rear hip range of motion during rear block contact was moderately correlated with normalised block power (*r* = 0.49, 90% confidence limits = 0.08 to 0.76; Table 1) and the rear hip angle at block exit was highly correlated with normalised block power (*r* = 0.60, 90% confidence limits = 0.23 to 0.82). A greater push duration with the rear leg (as a percentage of total block phase duration) was also highly correlated with greater levels of normalised block power (*r* = 0.53, 90% confidence limits = 0.13 to 0.78).

****Table 1 near here****

****Figure 1 near here****

Data from the first flight phase and first stance touchdown are presented in Table 2. There were unclear relationships between normalised block power and the subsequent flight duration and each of the stance leg joint angles at touchdown. There was a moderate positive relationship between normalised block power production and normalised step length (*r* = 0.36, 90% confidence limits = -0.08 to 0.68), and a moderate negative relationship between normalised block power and normalised touchdown distance (*r* = -0.46, 90% confidence limits = -0.74 to -0.04).

****Table 2 near here****

Discussion

We investigated the angular kinematic patterns of the lower limbs during the block phase and aimed to understand specific aspects of technique that were associated with higher levels of block phase performance. The main findings were that improved block phase performance was associated with increased contributions from the rear leg, particularly the hip, and also the angular velocity of the front hip. Furthermore, higher levels of block phase performance did not negatively affect first stance touchdown kinematics. The high intraclass correlation coefficients provide confidence in the reliability of the presented data with respect to the within-sprinter variability relative to the total between-sprinter variability (Vincent & Weir, 2012).

The very high negative relationship (*r* = -0.72) between 100 m PB time and normalised block power reiterates previous findings that sprinters with faster PB times are also typically better starters (Baumann, 1976; Mero, 1988; Mero et al., 1983). However, the imperfect correlation reinforces that block phase technique should be compared against current performance from just the phase of interest, not previous performance measures, particularly those which include subsequent phases of a sprint (Bezodis et al., 2010). The unclear correlations between ‘set’ position joint angles and normalised block power (Table 1) suggest that block positioning is not likely to be an important differentiating factor between sprinters of different performance levels, and thus a single optimal ‘set’ position cannot be recommended. This supports previous research where relatively large standard deviations have commonly been observed in ‘set’ position kinematics, even within relatively homogeneous groups of sprinters (Atwater, 1982; Mero, 1988; Mero et al., 1983).

The proximal-to-distal pattern of peak front leg joint angular velocities (Figure 1) is consistent with the data presented by Slawinski et al. (2010b) and suggests these sprinters used a strategy commonly adopted in power demanding tasks, which is to transfer power distally using the biarticular muscles. With such a strategy, as each joint approaches full extension, its deceleration is largely achieved using the biarticular flexor muscles to absorb rotational energy and transfer it distally to assist extension at the next distal joint rather than using the mono-articular flexor muscles which would dissipate the energy (Bobbert & van Ingen Schenau, 1988; Gregoire, Veeger, Huijing, & van Ingen Schenau, 1984). A proximal-to-distal strategy was not used when extending the rear leg where the knee joint angular velocity peaked first (Figure 1), again consistent with Slawinski et al. (2010b). This may be due to the rear knee joint starting from a more extended angle in the ‘set’ position, limiting its range and duration of extension (Table 1). This could affect the overall force producing capability of the rear leg due to changes in the gastrocnemius muscle-tendon unit length (Mero, Kuitunen, Harland, Kyröläinen, & Komi, 2006) and the consequent effects of the force-length relationship (Guissard, Duchateau, & Hainaut, 1992; Mero et al., 2006). Ultimately, these group-wide findings highlight the asymmetrical nature of the sprint start and its demands. As it has previously been shown that the choice of rear block leg can affect both reaction time and push phase duration due to hemispheric specialisation (Eikenberry et al., 2008), consideration should be given to this in training programmes focussing on both block phase technique (e.g. Vagenas & Hoshizaki, 1986) and physical development.

Whilst there were consistent group-wide trends in the joint angular velocity sequencing during the block phase, the lack of high correlations between discrete angular kinematic variables and normalised block power across the group of sprinters highlighted that there was generally no single aspect of technique that was critical for success. However, the moderate correlations between normalised block power and peak angular velocity of both hip joints (both r = 0.49) suggest that rapid hip extension should be one of the first things to consider when addressing a sprinter's technique during the start. This increased rate of hip extension could explain the greater rate of external force development previously observed by Slawinski et al. (2010a) in higher level sprinters during the early part of the block phase compared to their less able counterparts. A relatively early extension of the hips may be important for rapidly increasing force generation from movement onset, generating power which is transferred distally down the front leg in particular. Furthermore, the relationship between normalised block power and change in rear hip angle during rear block contact (r = 0.49), but also with the rear hip angle at block exit (r = 0.60), suggest that greater rear hip extension, in particular through the higher end of its range of motion, may be important for generating greater block power. The high positive relationship between push duration with the rear leg (as a percentage of total block phase duration) and normalised block power (r = 0.53) reinforces previous suggestions regarding the importance of rear leg force generation (Lemaire & Robertson, 1990; Payne & Blader, 1971; van Coppenolle et al., 1989), and the above relationships between rear hip extension and normalised block power suggest that hip extension may be an important feature in achieving this. Findings from a recent experimental study by Slawinski et al. (2013) suggest that front and rear hip angular velocity can be altered by manipulating block spacing. Whilst our data suggest that there appears to be no optimal 'set' position that is applicable for all sprinters, and strength limitations must also be considered, it is possible that alterations to block spacing could be used as an acute means through which to improve performance if a sprinter is identified as exhibiting relatively slow hip extension.

Beyond block exit, large inter-participant variation in stance leg joint angles existed at first touchdown (Table 2). These stance leg configurations at touchdown affected touchdown distance which can have a considerable effect on a sprinter's ability to generate propulsive force during stance. A smaller negative touchdown distance means that the CM must be rotated further in front of the stance foot prior to leg extension for this extension to propel the sprinter in a more favourable horizontal direction (Bezodis, Salo, & Trewartha, 2008; Jacobs & van Ingen Schenau, 1992). Whilst the relationship between normalised block power and the subsequent flight duration was unclear, there existed moderate correlations with normalised touchdown distance (r = -0.46) and normalised step length (r = 0.36). Both of these relationships are potentially favourable for performance; striving to produce greater power during the block phase therefore does not appear to inhibit subsequent technique in a sprint and may actually be associated with landing in a better position at touchdown.

Data were collected non-invasively at athletes' planned training sessions. The collection of data during competition would clearly be of interest but the possibility of this is limited due to access constraints (particularly when studying world-class sprinters) as well as the number of athletes (outside lane(s) only) and repetitions (often only one sprint) that could be studied. In the current study, data were collected as close to the competition phase of the season as possible and no changes were made to the sprinters' training programme. Where access permits, future research could also study the physical attributes across a cross-section of sprinters to investigate their influence on some of the technical aspects highlighted in this study.

The 'set' position of a sprinter in the blocks does not appear to be an important differentiating factor between sprinters of different performance levels. The joints of the front leg typically extended over a considerable range of motion in a proximal-to-distal extension pattern, and correlations suggested that greater peak hip joint velocity was associated with increased external power production. The rear leg joints extended over a smaller range, but a longer rear leg push as a percentage of total push phase duration was associated with higher levels of external power production during the block phase. Greater rear hip extension and rate of extension during the block phase was also associated with higher levels of external power production. As higher levels of power production during the block phase were not subsequently associated with any potentially disadvantageous aspects of technique at the onset of the first stance phase, sprinters should be encouraged to maximise the rate of extension at both hips during the block phase in an attempt to achieve maximal power production.

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Tables

Table 1. Group mean and standard deviation values for trunk and lower limb joint angles in the ‘set’ position and their ranges of motion during the respective block contact, reliability of these values, and their relationships (including 90% confidence limits) with normalised average horizontal external block power.

	Set position angle (°)				Range of motion during block exit (°)			
Joint or segment	Mean ± *s*	ICC	Relationship with block power		Mean ± *s*	ICC	Relationship with block power	
			r	90% confidence limits			*r*	90% confidence limits
Trunk	-17 ± 4	0.89	0.16	-0.29 to 0.55	46 ± 8	0.94	0.09	-0.35 to 0.50
Rear hip	77 ± 9	0.97	0.05	-0.39 to 0.47	31 ± 13	0.97	0.49	0.08 to 0.76
Rear knee	109 ± 9	0.93	0.07	-0.37 to 0.48	18 ± 6	0.90	-0.18	-0.56 to 0.27
Rear ankle	111 ± 12	0.93	-0.17	-0.57 to 0.29	19 ± 9	0.95	0.04	-0.41 to 0.47
Front hip	47 ± 6	0.95	0.08	-0.36 to 0.49	113 ± 9	0.92	0.27	-0.18 to 0.62
Front knee	86 ± 5	0.89	0.11	-0.33 to 0.51	73 ± 7	0.90	-0.04	-0.46 to 0.39
Front ankle	107 ± 12	0.96	-0.07	-0.48 to 0.37	36 ± 10	0.95	0.004	-0.42 to 0.43

The intraclass correlation coefficients (ICC) were calculated using model 2,3 to quantify the reliability of these data with respect to the within-sprinter variability relative to the total between-sprinter variability.[16] Pearson’s correlation coefficients (*r*) were calculated between each of these discrete variables and normalised average horizontal external block power (‘block power’). The 90% confidence limits were determined using the Fisher z transformation.[17] Trunk angle is presented relative to the horizontal with a negative value representing the shoulders below the hips. Ranges of motion during block exit for the rear leg joints are during rear block contact only.

Table 2. Group mean and standard deviation values for selected kinematic variables from the first flight and first stance phases, reliability of these values, and their relationships (including 90% confidence limits) with normalised average horizontal external block power.

	Mean ± *s*	ICC	*r*	90% confidence limits
Flight duration (s)	0.073 ± 0.022	0.99	0.20	-0.25 to 0.58
Normalised step length	1.10 ± 0.07	0.92	0.36	-0.08 to 0.68
Normalised touchdown distance	-0.20 ± 0.07	0.94	-0.46	-0.74 to -0.04
Hip angle at touchdown (°)	95 ± 9	0.90	0.11	-0.33 to 0.51
Knee angle at touchdown (°)	101 ± 7	0.89	-0.10	-0.51 to 0.34
Ankle angle at touchdown (°)	96 ± 7	0.95	0.31	-0.13 to 0.65

The intraclass correlation coefficients (ICC) were calculated using model 2,3 to quantify the reliability of these data with respect to the within-sprinter variability relative to the total between-sprinter variability.[16] Pearson's correlation coefficients (*r*) were calculated between each of these discrete variables and normalised average horizontal external block power. The 90% confidence limits were determined using the Fisher *z* transformation.[17] The normalised values were divided by leg length.[15] Touchdown distance represents the horizontal distance between the CM and the stance leg metatarsal-phalangeal joint at touchdown with a negative value representative of the metatarsal-phalangeal joint behind the CM.

Figure 1. Joint angular velocities throughout the push phase for a) rear ankle, b) rear knee, c) rear hip, d) front ankle, e) front knee and f) front hip. Positive values represent joint extension. The bold line represents the mean of all sprinters and the dotted lines represent each individual sprinter's mean data. The dotted vertical line in figures a-c represents the mean time of rear block exit and the shaded area represents the range in this variable across all sprinters. The values in the top right hand corner of each figure are the strength and 90% confidence limits of the relationships between the peak angular velocity at each joint and normalised average horizontal external block power across all of the sprinters.