KINETIC DETERMINANTS OF ATHLETICS SPRINT START PERFORMANCE

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The sprint start lays a foundation to a good performance of track athletes. Thus, the aim was to understand the key force production determinants of the athletics sprint start. Eleven male athletes performed normal sprint starts with ground reaction forces collected at 1000 Hz from under each extremity separately. Key kinetic variables were analysed from six starts from each athlete and correlated with the horizontal external power. Several force and timing variables provided statistically significant correlations, but especially the high ratio of forces at 58.9 ± 3.5% with r = .941 (p = .000) demonstrated the importance of horizontal force production during the start. Better performers reached large forces on the blocks quicker, although it was interesting that the actual rate of force production did not statistically significantly correlate with the horizontal external power.

KEY WORDS: forces, power, sprinting, track and field, correlation

INTRODUCTION: The sprint start lays a foundation to a good acceleration and consequent performance of track athletes. Therefore, researchers have shown interest in understanding how athletes perform their start. The outcome measure has typically been time to a certain distance or the horizontal velocity at block exit. As Bezodis et al. (2010) explained, time to a certain distance is influenced by other issues than just the start itself, and velocity at block exit can be misleading due to the impulse being potentially increased by longer push times against the blocks. The latter was highlighted in data by Willwacher et al. (2013), when the men's slow group left the blocks with higher velocity than either men's fast or world-class group, but the world-class group had substantially lower block time than the other two groups. In fact, the men's slow group had 9.0% and the fast group 6.5% higher velocity at block exit than the world-class group, while the respective block times were 17.6 and 14.7% longer (Willwacher et al., 2013). As Bezodis et al. (2010) advocated, the horizontal external power seems to be, also based on the above, the most appropriate outcome measure. However, there are only a limited number of studies, which have used horizontal external power as the key variable against which the performances have been assessed.
Separate force plates on instrumented blocks (Willwacher et al., 2013) or using two force plates (Salo et al., 2016) have allowed the forces applied by each leg during the sprint start to be assessed. However, when measuring the kinetics of sprint start, a challenging issue is to get comprehensive data, as instrumented blocks or the two force plate setting cannot provide direct measurements from the arms' ground reaction forces in the early push phase. Graham-Smith et al. (2014) demonstrated that the omission of the arms' contribution made substantial differences to vertical impulse and the centre of mass projection angle for a single participant, although the influence of arms' ground reaction forces in the horizontal direction was rather small. Moreover, Mero et al. (2006) have used the settings where ground reaction forces for each leg and arm were measured separately for a group of competitive sprinters.
Overall, it is worth revisiting the sprint start across a number of participants by collecting comprehensive kinetic data utilising horizontal external power as the key outcome variable. Thus, the aim of this study was to understand the key force production determinants for the sprint start in track and field athletics.

METHODS: Eleven male sprinters and sprint hurdlers provided informed consent to participate in the study following the institutional ethical approval. The participants' mean and SD of age were 22.8 ± 3.3 years, height 1.83 ± 0.08 m and mass 77.7 ± 8.6 kg. All had an officially recorded 100-m personal best time (10.73 ± 0.29 s, range 10.34 to 11.20 s). Four force plates (900 mm x 600 mm, sampling at 1000 Hz, model 9287BA; Kistler Instruments Ltd, Switzerland) positioned in a 2-by-2 formation were covered with synthetic rubber mats. To allow forces from each leg to be collected separately, competition blocks were set in the same way as reported by Salo et al. (2016), whereby two separate spines were used, one on each force plate with the foot plates positioned so that the lateral space between them equalled the width of the spine. The remaining two force plates captured ground reaction forces under the arms. The athletes conducted a self-selected warm-up including some practice starts. All participants used their own preferred block settings and spikes were worn throughout. An experienced starter provided normal starting commands followed by an electronic beep, which synchronously triggered the force plate data collection and provided a starting signal. Each participant performed seven to eight maximal-effort sprint starts with a four-minute recovery between each trial.

The force data were analysed using a custom-written Matlab script (The MathWorks, USA), which firstly filtered the data using a fourth-order Butterworth filter (103-Hz cut-off frequency based on residual analysis). Ground reaction forces from the four platforms were summed in the vertical and anterior-posterior (considered horizontal hereafter) directions. The average and standard deviation of vertical force was then calculated across the first 50 ms from the starting signal. Onset of movement was defined as the instant when vertical force exceeded a two standard deviation threshold above the average. Thus, the reaction time was not taken account in any of the calculated variables. Block exit was set at the instant vertical force fell below 20 N. The impulse-momentum relationship was then used to calculate vertical and horizontal block exit velocities. The time between onset of movement and block exit was defined as total push duration and combined with horizontal block exit velocity to provide horizontal external power as the criterion (Bezodis et al., 2010). This horizontal external power was body-mass normalised. Subsequently, average horizontal and total (resultant) forces were calculated across the push duration and used to calculate ratio of forces (Morin et al., 2011). Maximum forces (horizontal and vertical) were also computed for each leg (front and rear). Finally, peak rate of horizontal force development (RFD) for each leg was calculated across the first 150 ms of force production using a 30-ms moving window. All force, rate of force development and horizontal external power variables were normalised to body mass. Additionally, the difference between rear and front leg maximum force production both horizontally and vertically were calculated, as well as the time difference to achieve these maximum forces in respective directions.

The six best starts (based on horizontal external power) for each athlete were averaged and consequently used to calculate the relationships between the above variables and the horizontal external power across the 11 participants (Pearson correlations, SPSS Statistics v. 22). Statistical significance was set at $p<.05$.

RESULTS: The average horizontal block exit velocity across the athletes varied from 3.22 to 3.70 $m \cdot s^{-1}$ (mean ± SD: 3.45 ± 0.16 $m \cdot s^{-1}$). With the total push duration of 0.406 ± 0.038 s, this resulted in the normalised horizontal external power of 14.17 ± 2.03 $W \cdot kg^{-1}$ (range: 11.78 – 19.07 $W \cdot kg^{-1}$). Both the horizontal block exit velocity and push duration were statistically significantly correlated with the horizontal external power (r = .714, p = .014 and r = -.705, p = .015, respectively). Other statistically significant correlations with the horizontal external power are presented in Table 1 below. The rate of force development yielded non-significant results (r = .502, p = .115 for the rear leg and r = 0.156, p = .648 for the front leg).

DISCUSSION: This study analysed key force production variables across a range of competitive athletes. It is not surprising that the horizontal block exit velocity was positively and statistically significantly, and the push duration negatively and statistically significantly correlated with the horizontal external power, as the block exit velocity is in nominator and push duration in denominator of the average power equation. The block exit velocities in this study (range 3.22 to 3.70 $m \cdot s^{-1}$) were slightly lower than those in Willwacher et al. (2013), where mean values of 3.54, 3.77 and 3.86 $m \cdot s^{-1}$ were reported for different male groups. The

Table 1. Discrete kinetic variables, which had statistically significant correlations (Pearson *r*) with the normalised horizontal external power

	Mean	SD	*r*	*p*
Average resultant force on the blocks [$N\cdot kg^{-1}$]	14.5	0.7	.906	.000
Average horizontal force on the blocks [$N\cdot kg^{-1}$]	8.6	0.9	.958	.000
Maximum horizontal force; rear leg [$N\cdot kg^{-1}$]	11.3	1.8	.698	.017
Maximum vertical force; rear leg [$N\cdot kg^{-1}$]	10.0	1.6	.658	.028
Maximum horizontal force; front leg [$N\cdot kg^{-1}$]	11.2	1.3	.610	.046
Time of maximum horizontal force; front leg [s]	0.336	0.034	-.783	.004
Time of maximum vertical force; front leg [s]	0.333	0.035	-.809	.003
Time difference of maximum horizontal forces [s]	0.221	0.026	-.623	.040
Time difference of maximum vertical forces [s]	0.214	0.021	-.813	.002
Ratio of forces (%)	58.9	3.5	.941	.000

reason may be that Willwacher et al. (2013) could not measure the initial negative impulse from the arms with their set up. Thus, while the arms did not provide any statistically significant correlation with the horizontal external power in this study, the importance of the inclusion of all ground reaction forces to comprehensively analyse sprint start cannot be ignored. On the other hand, our results ($3.45 \pm 0.16\ m\cdot s^{-1}$) were slightly higher than reported by Mero et al. (2006) for a group of similar 100-m sprinters ($3.39 \pm 0.23\ m\cdot s^{-1}$ and $3.30 \pm 0.21\ m\cdot s^{-1}$ for two different block settings). The reason for this difference could be that Mero et al. (2006) fixed the block angles, while in the current study the athletes used their preferred block angles. Thus, overall the block exit velocities and performances in this study seem to be in line with these other studies.

Velocity on the blocks is created via impulse and thus again it is logical that some key horizontal force variables were positively correlated with the external horizontal power. Negative correlations of time to achieve maximum forces on the front leg with the horizontal external power also emphasise that the key is not solely to obtain large forces, but the forces have to be produced quickly due to a time penalty in the power equation to gain large impulses through increased contact time. This supports Willwacher et al. (2013) findings that world-class athletes did not maximise their centre of mass acceleration during the blocks, but obtained better performances by trying to minimise the block time. There is, though, a difference between Willwacher et al. (2013) and our results in the context that in this study, better athletes (by the external power) were associated with increased block exit velocity, while world-class athletes in Willwacher et al. (2013), despite having a higher horizontal external power, had lower block exit velocity than men's other two groups. This difference between the studies highlights the danger of making too far-reaching conclusions based on your participant group. Considering the results in the current study, it would be easy to extrapolate that world-class athletes would leave the blocks with higher velocity. However, we did not have any real world-class athletes (the fastest 100-m personal best was 10.34 s). As Willwacher et al. (2013) results demonstrate, the real world-class athletes could perform differently than what extrapolation from the lower level athletes would indicate.

Perhaps more interesting results in this study were the variables which did not have statistically significant correlations with the horizontal external power. It can be assumed that explosive force production is the key based on the power equation and empirical data provided by Willwacher et al. (2013). Consequently, the maximum rate of force development in the horizontal direction was included in our analysis. This, though, is a challenging variable. When a tangent of the force curve is used, it has been shown not to be a very stable variable (McLellan et al., 2011), which was also the case in this study despite the filtering process. Literature contains different methods to calculate a RFD varying from a small time window to the overall average from the start of the force production to the maximum value. In the sprint start, however, especially the front leg seems functionally different from the rear leg, as it takes relatively long time to produce the maximum force. Thus, we utilised the average of a 30-ms window, which was moved every millisecond during the first 150 ms to find the peak value. This measure seemed to be a stable variable.

However, it was interesting that for such dynamic and powerful movement, the results were not statistically significantly correlated with the external horizontal power (r = .502, p = .115 for the rear leg and r = 0.156, p = .648 for the front leg).
It is perhaps logical that vertical force variables were not associated with the horizontal external power. On the other hand, one could assume that the athletes' functional capacities would be similar in both measured directions. As this was not the case, this reinforces the importance of producing force more horizontally at the start. The ratio of forces was strongly, positively and statistically significantly correlated with the horizontal external power, i.e. the larger the proportion of the horizontal force to the resultant force was, the higher the horizontal external power. The maximum ratio of forces in Morin et al. (2011) was reported as 42.4% for the first step. This is somewhat smaller than our average ratio of forces at 58.9%. However, this could reflect the fact that the start itself (with a double support phase from angled blocks) is functionally very different to that of the first step. Fortier et al. (2005) reported that better athletes produced significantly larger (34%) maximum force (perpendicular to the starting block) on the rear leg than slower athletes. Our correlational analysis supports the notion that actively using the rear leg during sprint start is important
Those who produced more normalised horizontal external power, produced maximum forces between the legs quicker than athletes who generated less normalised horizontal external power. This could be due to a co-ordination issue or that when you have more force, you can produce them more synchronously even in such asymmetric situation like the sprint start.

CONCLUSION: The results demonstrated that the better performers reached large forces on the blocks quicker than the others and actively used their rear leg. However, it was interesting that the actual rate of force production did not statistically significantly correlate with the horizontal external power. Additionally, the ratio of forces results together with the literature indicate for athletes and their coaches the importance of horizontal force production during the start. This may be emphasised with increased inclination of the block angles, although this was beyond the scope of the current study and warrants further investigation.

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