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Title

Understanding the track and field sprint start through a functional analysis of the external force features which contribute to higher levels of block phase performance

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Abstract

This study aimed to identify the continuous ground reaction force (GRF) features which contribute to higher levels of block phase performance. Twenty-three sprint-trained athletes completed starts from their preferred settings during which GRFs were recorded separately under each block. Continuous features of the magnitude and direction of the resultant GRF signals which explained 90% of the variation between the sprinters were identified. Each sprinter's coefficient score for these continuous features was then input to a linear regression model to predict block phase performance (normalised external power). Four significant ($p < 0.05$) predictor features associated with GRF magnitude were identified; there were none associated with GRF direction. A feature associated with greater rear block GRF magnitudes from the onset of the push was the most important predictor ($\beta = 1.185$), followed by greater front block GRF magnitudes for the final three-quarters of the push ($\beta = 0.791$). Features which included a later rear block exit ($\beta = 0.254$) and greater front leg GRF magnitudes during the mid-push phase ($\beta = 0.224$) were also significant predictors. Sprint practitioners are encouraged, where possible, to consider the continuous magnitude of the GRFs produced throughout the block phase in addition to selected discrete values.

Keywords

athletics, biomechanics, functional data analysis, kinetics, sprinting

Introduction

The start is an important component of a sprint because, although sprinters typically spend less than 0.4 s pushing against the blocks, they exit the blocks with velocities already around 30% of their maximum (Rabita et al., 2015). Whilst considerable research has focussed on block phase kinematics (e.g. Bezodis, Salo, & Trewartha, 2010; 2015; Mero, Luhtanen, & Komi, 1983; Slawinski et al., 2010; 2012; 2013), the underlying causes of motion are the forces which the sprinters generate during the block phase. In early studies of block phase forces, both Baumann (1976) and Mero et al. (1983) identified that groups of sprinters with faster 100 m personal best (PB) times produced greater total horizontal impulses during the block phase than groups comprising their lower-performing counterparts. The groups of faster sprinters produced these greater impulses with similar or shorter block phase durations than the slower sprinters, and thus their average horizontal force production was greater.

Sprinters commence the block phase with four separate points of contact. After reacting to the starting signal, both hands soon leave the track, followed by the foot placed in the rear block, and the block phase ends when the front foot leaves its starting block. Since the early studies of Baumann (1976) and Mero et al. (1983), subsequent studies have separated the block phase forces into those applied against each of the blocks. Hafez, Roberts and Seireg (1985) investigated the front block forces and identified that the direction of force application may be an important consideration but this has not been directly explored beyond their exploratory analysis of four university-level sprinters. At the rear foot, block contact lasts for the first 40-60% of the block phase (Bezodis et al., 2015), and thus the rear leg contributes only around 24-34% of the total block phase impulse (Čoh, Peharec, &

Bacic, 2007; Guissard & Duchateau, 1990). However, larger peak forces have been found to be generated at the rear block than the front block within a group of sprinters with 100 m PBs of 10.8 to 11.2 s (Guissard & Duchateau, 1990) and in two World Championships finalists (van Coppenolle, Delecluse, Goris, Bohets, & Vanden Eynde, 1989). It has therefore been suggested that greater rear block force generation may also be a distinguishing feature of higher performing sprinters (Fortier, Basset, Mbourou, Faverial, & Teasdale, 2005; van Coppenolle et al., 1989).

Willwacher et al. (2016) recently extended the understanding of block phase kinetics by analysing the average and peak block forces and total block impulses produced against each block in the three principal directions by 154 sprinters of both sexes across a wide range of performance levels (100 m PBs of 9.58 to 14.00 s). Five underlying force-application factors which explained 86% of the variance in block phase performance were identified by Willwacher et al. (2016). In support of the aforementioned suggestions and evidence, Willwacher et al. (2016) found that the factor most predictive of block phase performance levels was associated with the magnitude of force application against the rear block (standardised regression coefficient = 0.040). This was followed in importance by factors associated with the ratio of propulsive to resultant impulse against the front block (0.032), the peak and average force magnitudes against the front block (0.030 and 0.026, respectively), and finally by a factor associated with the ratio of propulsive to resultant impulse against the rear block (0.010). Although their quantitative analysis was restricted to peak or averaged characteristics of the underlying force signals, Willwacher et al. (2016) also qualitatively compared the mean front block resultant force traces between the 10 sprinters with the highest and lowest scores for two selected factors, and suggested that these continuous time-histories may illustrate differences in strategy between higher and lower performing sprinters within each factor. Willwacher et al. (2016) highlighted that future studies should investigate these potentially different block phase strategies in greater depth. Functional data analysis techniques provide an approach which enables the variability in continuous functions to be described and used as inputs to assess associations with dependent measures, rather than inputting the more traditional predetermined discrete values (Warmenhoven et al., 2017). Such an approach is therefore suitable for addressing the recommendations of Willwacher et al. (2016) using continuous block phase force signals, and could yield new insights regarding the underlying kinetic features of a successful block phase. Our aim was therefore to identify and explain the continuous features of the magnitude and direction of force application which contribute to higher levels of block phase performance. Based on the results of the discrete analysis of Willwacher et al. (2016), we hypothesised that features of the rear block force magnitude would be the most important predictor of block phase performance, followed in importance by features of the direction of force application on the front block, front block force magnitudes, and direction of force application on the rear block.

Methods

Participants

Twenty-three male sprint start-trained athletes (sprinters, long jumpers, triple jumpers, decathletes; mean ± SD: age = 20 ± 1 years; height = 1.73 ± 0.04 m; mass = 66.6 ± 4.0 kg; 100 m PB = 11.37 ± 0.37 s) provided written informed consent to participate in this study which was approved by the research ethics committee of the

National Institute of Fitness and Sports in Kanoya. All sprinters had prior experience of using starting blocks.

Protocol

Each sprinter completed two maximal effort 60 m sprints from starting blocks on a single day. All sprinters were injury free and fully rested at the time of testing, and at least 10 minutes of rest were provided between sprints to ensure adequate recovery. Each sprinter wore their own spiked shoes and positioned the blocks to their own personal preference. Following standard “on your marks” and “set” commands, each sprint was initiated by an electric starting gun which emitted an auditory signal and initiated data collection. Ground reaction force (GRF) data were collected at 1000 Hz from under each block and each hand using four synchronised force platforms (TF-3055, TF-32120, Tec Gihan, Uji, Japan) located as depicted in Figure 1.

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

Data processing

The raw medio-lateral (F_X), antero-posterior (F_Y) and vertical (F_Z) GRF signals from each of the four force platforms were imported to Matlab (R2015a, Natick, USA). Movement onset was identified from the sum of all raw F_Z data by determining the mean and standard deviation of total F_Z during the 0.075 s immediately following the start signal (i.e. less than the likely minimum neuromuscular-physiological component of reaction time of 0.085 s; Pain & Hibbs, 2007), and then identifying the instant where the raw F_Z data first exceeded two standard deviations above the mean value and remained above this threshold for greater than 0.05 s. The instants when the front and rear hands (i.e. the hands on the corresponding side of the body to the leg in the front and rear block) left the track were identified from the raw three-dimensional resultant force data from each of the force platforms under the hands using a threshold of 10 N. The instants when the rear and front feet each left the blocks were identified from the raw three-dimensional resultant force data from each of the force platforms under the respective blocks using a threshold of 30 N. This yielded five events for each sprint: movement onset, front hand off, rear hand off, rear block exit, front block exit.

Each of the 12 raw GRF signals (i.e. F_X, F_Y and F_Z for each foot and hand) were then truncated immediately after their respective hand off/block exit frame, and were padded with 50 points at each end using the reflection method (Smith, 1989). These padded signals were low-pass filtered at 50 Hz using a 4th-order Butterworth digital filter, after which the data between movement onset and the respective endpoint for each signal (i.e. hand off or block exit) were extracted. For the rear foot and both hands, the filtered GRF signals were extended with zeroes from their final frame until front block exit so that all 12 signals were equal in length for a given trial.

The sum of the four F_Y signals was used to calculate average horizontal external power between movement onset and front block exit as an objective measure of block phase performance (Bezodis et al., 2010). Firstly, instantaneous horizontal acceleration was determined as F_Y divided by mass, and this was integrated with respect to time to obtain the change in horizontal velocity. Cumulative horizontal velocity was determined, and external power was calculated as the product of F_Y and horizontal velocity. The average horizontal external power between movement onset and front block exit was calculated, and normalised average horizontal external power (NAHEP) was calculated according to the procedures outlined by Bezodis et al. (2010). The trial with the highest NAHEP was identified for each sprinter, and data from this trial were used in all subsequent analyses.

Although the hands assist in the support of bodyweight during the “set” position, they contribute minimally to the kinetics beyond movement onset - the combined antero-posterior impulse from both hands is less than 0.2% of the combined anterior-posterior impulse generated by the two legs during the block phase (Otsuka et al., 2014). Furthermore, as medio-lateral forces do not predict block phase performance (Willwacher et al., 2016) and are low in magnitude compared with the antero-posterior and vertical forces (Figure 2), we utilised the antero-posterior and vertical forces from underneath each of the two blocks in the subsequent functional data analysis in order to achieve our aim. Four signals from each trial were therefore input to the functional data analysis: one which quantified each of the magnitude and direction of the force produced against each of the two blocks (Figure 3). The magnitude of the resultant force in the sagittal plane (F_R) under each of the two blocks was determined from the filtered F_Y and F_Z data from the respective force platform. The ratio of forces (RF) for each block was determined from the filtered F_Y and F_Z data from the respective force platform using the calculation of Morin, Edouard and Samozino (2011): a RF value of 0% corresponded to vertically directed force and 100% to horizontally directed force.

All processed force signals (F_X, F_Y and F_Z for both hands, and F_X, F_Y, F_Z, F_R and RF for both feet) for the best trial of each of the 23 sprinters (Figure 2) were expressed relative to bodyweight and resampled at 101 evenly spaced intervals between movement onset and front block exit using an interpolating cubic spline. In order to yield appropriate input data for the functional data analysis given the non-cyclical nature of a block start, the data point of the rear foot RF signal (Figure 3a) from the final frame prior to rear foot block exit was replicated up to front foot block exit (Warmenhoven et al., 2017).

Statistical analysis

A 23 × 101 matrix was formed for each force signal with each column representing an individual sprinter's signal. A singular-value decomposition of these matrices was then performed using the python package NumPy (http://www.numpy.org/). This resulted in 23 modes (principal components) for each force signal and individual coefficients for each mode for each sprinter. The combination of these 23 modes with their respective coefficients for each sprinter enabled that sprinter's signal to be represented. The number of modes which explained at least 90% of the variation in each of the four input signals was identified, and these were retained for further analysis (Smith, Roberts, Kong, & Forrester, 2017). To determine how much of the between-sprinter variance in block phase performance was explained by each of these individual modes, sprinters' coefficient scores for these modes were used as predictor variables in a forward stepwise linear regression model in which NAHEP was the outcome variable. The modes which were significant ($p < 0.05$) predictor variables were identified, and their relative contribution was quantified based on the corresponding standardised β coefficient. To better visualise each of the modes which were significant predictors of performance, the effect of a ± 1 *SD* change from the mean coefficient score on the respective underlying mean force signal was visualised (Figure 4). Qualitative biomechanical interpretations of these effects were then determined (Table 2) in line with the procedures of Smith et al. (2017).

Results

The mean ± *SD* average horizontal external power during the push phase was 832 ± 113 W (NAHEP = 0.43 ± 0.06). This was associated with a mean ± *SD* horizontal centre of mass block exit velocity of 3.12 ± 0.21 $m \cdot s^{-1}$ and a mean ± *SD* push phase duration of 0.391 ± 0.038 s. 90% of the variation in the 23 individual sprinters' signals was explained by four modes for the RF signals at both blocks and the F_R signal on the rear block, whereas five modes were required to explain 90% of the variance in the front block F_R signal (Table 1).

****Figure 2 near here****

****Figure 3 near here****

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

A regression model (F = 38.732, $p < 0.001$) with four significant predictor variables (modes 1 and 3 of the rear magnitude signal, modes 1 and 4 of the front magnitude signal) predicted 87.3% (adjusted R^2) of the variance in NAHEP. Based on the standardised β coefficients, rear magnitude mode 1 had the greatest relative contribution ($\beta = 1.185$, p < 0.001) to NAHEP, followed by front magnitude mode 1 ($\beta = 0.791$, p < 0.001), rear magnitude mode 3 ($\beta = 0.254$, p < 0.01), and front magnitude mode 4 ($\beta = 0.224$, $p < 0.01$). The effect of a ± 1 *SD* change in score for each of these four modes on the respective underlying force signals are illustrated in Figure 4 and their qualitative interpretations are presented in Table 2.

****Figure 4 near here****

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

Discussion

We aimed to identify features of the GRF time histories which contribute to higher levels of block phase performance during the sprint start. Our hypothesis was partly supported - although it was found that features associated with the resultant magnitude of the GRFs on the rear block were the most important predictor of block phase performance (based on the standardised β coefficients), this was followed in importance by front block force magnitude features, whilst features related to the direction of application of these forces were not significant predictors of performance. The two most important predictors were both associated with greater resultant force production throughout the entire time that each foot was pushing against its respective block (Figures 4a and 4b), identifying that it is the ability to generate greater forces throughout the block phase, not just greater peak forces, which are associated with higher levels of block phase performance.

The generation of greater forces against the rear block was the strongest significant predictor of performance (Figure 4a; Table 2). Although the rear leg contributes less impulse due to its shorter pushing duration (Čoh et al., 2007; Guissard & Duchateau, 1990), this importance is consistent with the findings of Willwacher et al. (2016). In a group-based design, Čoh, Peharec, Bacic and Mackala (2017) also found that a faster group of sprinters (mean 100 m PB = 10.66 s) produced greatest resultant forces against the rear block than a group of their slower counterparts (mean 100 m PB = 11.00 s). This combination of empirical cross-sectional and group-based evidence supports long standing suggestions (Payne & Blader, 1971) and case-study based evidence (van Coppenolle et al., 1989) relating to the importance of a forceful rear leg action in the blocks. However, it is important that focussing on maximising this rear leg action does not affect the contribution from the front leg, since the front leg contributes 66-76% (mean = 74% in our study) of the total block phase impulse (Čoh et al., 2007; Guissard & Duchateau, 1990) and was found to be the next most important predictor in our study (Figure 4b, Table 2) as well as the next three most important factors (front leg force direction, front leg maximal forces, front leg average forces) by Willwacher et al. (2016).

Our findings and those of Willwacher et al. (2016) identify that the most important predictor of block phase performance is the ability to generate greater rear block force *per se*, but not the ability to direct these forces in a more horizontal direction. However, whilst we then found the second strongest predictor to be front block force magnitudes, Willwacher et al. (2016) found it to be the ratio of front block propulsive to resultant impulses. Furthermore, in other studies of block phase forces, Otsuka et al. (2014) found the direction of the force vector to distinguish between groups of well-trained, less trained, and novice sprinters, whilst Salo et al. (2017) found that ratio of forces averaged across both blocks, as well as larger horizontal and vertical peak rear block forces, and larger and earlier peak horizontal front block forces, were all significantly related to NAHEP. This combination of results suggests that ratio of force differences at any single time point may not be sufficiently important, but when averaged across the entire block phase (Otsuka et al., 2014; Willwacher et al., 2016; Salo et al., 2017) their role may be considered more important. However, it is also possible that there is a limit to the benefits of a more horizontally directed force vector during the block phase, possibly because of the unavoidable requirement to support bodyweight and raise the centre of mass.

The differing findings discussed above also highlight that there is not one simple relationship between block phase force production and performance. This could be explained by a range of factors including, but not limited to, study design (e.g. group-based versus cross-sectional or the analysis of a single best sprint versus the average of multiple sprints), the ability level of the studied participants, the training methods of the groups studied (which could influence factors ranging from specific strength characteristics to typical starting block spacings and obliquities), the model of starting blocks used, as well as the type of data analysis performed (i.e. discrete versus continuous). Firstly, as explained by Salo et al. (2017), caution should be applied before extrapolating findings beyond the studied participants group(s) and outside of the context of the design of the study. Secondly, these factors also identify potential avenues for future research such as the effect of different designs of starting block (which only have to conform to the ‘general specifications’ under IAAF rule 161.2), or specific strength characteristics, on the force production characteristics during the block phase. Thirdly, the dependent performance measure used must also be considered. Whilst NAHEP is an objective measure of block phase performance

(Bezodis et al., 2010), it is determined from the horizontal forces as it is intended to reflect sprint performance (which requires horizontal translation), rather than being a true measure of the total scalar power produced by a sprinter in the blocks, and it could therefore be biased when the horizontal GRF component is included in the analysis. Using the resultant force magnitude and direction overcomes this potential limitation. Finally, it must also be considered that the separate force measures (i.e. horizontal, vertical and resultant force magnitudes) included in the previous analyses are likely collinear as they are components of a single force vector, whilst the discrete measures extracted (i.e. peak and average forces) are also not entirely independent. We therefore believe that the functional analysis of a signal which corresponds to the magnitude of the force and a signal which corresponds to its direction, as we have used in the current study, provides an appropriate methodological framework.

Our functional data analysis enabled us to identify specific features of block phase force production which may not be apparent in the analysis of average or peak forces. For example, another feature of the rear block force magnitude mode 1 was that it was greater from the very onset of the pushing phase (Figure 4a, Table 2). This indicates that a greater force magnitude against the rear block in the “set” position (normalised to account for body weight) was associated with higher levels of block phase performance. It was first suggested by Baumann (1976) that a ‘spring tension’ in the “set” position could be an important feature of performance, and Mero et al. (1983) also suggested that a ‘pretension’ against the blocks may be beneficial. Whilst Gutiérrez-Dávila, Dapena and Campos (2006) found no increases in block exit velocity from an experimentally-manipulated ‘pretensed’ “set” position, theirs was an acute intervention with only brief familiarisation on the day prior to their experiment. Our findings, combined with those of Mero et al. (1983), provide evidence to suggest that the habitual adoption of a more ‘pre-tensed’ rear foot “set” position, or learning to adopt this position over time, may be associated with superior block phase performance. Longitudinal studies designed to directly address this are required to confirm this suggestion.

Other features of the rear block force magnitude which were associated with higher levels of block phase performance were features of the rear block force magnitude mode 3: an earlier peak and a later rear block exit as a percentage of total push phase duration (Figure 4c, Table 2). A relatively later rear block exit has been identified in groups of faster sprinters compared to their slower counterparts (Fortier et al., 2005; Slawinski et al., 2010), for faster national-level sprinters in a multiple case-study design (van Coppenolle et al., 1989), and as a positive correlate of higher block phase performance levels (r = 0.53) across a group of 16 sprinters (Bezodis et al., 2015). Spending more time pushing with the rear leg against the blocks therefore appears to be a feature of higher performing sprinters during the block phase. However, it must be considered that there is a likely limit to this duration so that sufficient time is allowed for limb repositioning as the rear foot must translate forwards to become the first foot which contacts the track.

The final significant predictor mode was a feature of the front block GRFs and was associated with a later initial rise in force, but to a higher magnitude during the time whilst the rear foot is also pushing (Figure 4d, Table 2). This was then followed by a slower rise to, and lower peak in, maximum force. Although this was the least important of our four significant predictor modes, it aligns with the qualitative analysis of Willwacher et al. (2016) which suggested that some sprinters may benefit from attaining higher force magnitudes during the first half of the block phase rather than solely focussing on achieving a high peak force magnitude. Our functional data analysis adds quantitative support to this notion, and suggests that maintaining a forceful push with the front leg during the time towards the end of the rear leg push may be another important feature of block phase technique.

As discussed earlier, our results may not necessarily be generalisable beyond the ability level of our studied cohort. Although we included decathletes and horizontal jumpers in this study, all participants were well-trained in the block start and competed in competitive 100 m races as part of their event (decathletes) or their periodised training (jumpers). Whilst we did not measure the kinematics of the sprinters during the block phase, or their physical attributes, the external forces which we measured are the direct causes of movement and are of direct importance for the levels of block phase performance achieved. For practitioners and researchers seeking to achieve some of the changes to block phase kinetics which we identified as significant predictors of block phase performance, there are specific evidence-based manipulations to “set” position kinematics which could be initially considered. For example, less vertically inclined block pedals could be used to increase the magnitudes of forces produced (Guissard, Duchateau, & Hainaut, 1992; Mero, Kuitunen, Harland, Kyröläinen, & Komi, 2006) or to increase the duration of the rear block push (Mero et al., 2006), whilst block spacings could also be manipulated to reduce the front and rear knee angles which have both been associated with greater block phase performance due to increased force production (Ciacci, Merni, Bartolomei, & Di Michele, 2017; Milanese, Bertucco, & Zancanaro, 2014). Finally, these kinematic changes could be considered alongside physical changes to enhance the ability to produce greater resultant joint moments at both ankles and the front hip, as well as joint power at the front knee, all of which have been associated with greater average force production in the blocks (Brazil et al., 2018).

In summary, we found that features of the resultant magnitudes of the GRFs produced against both of the blocks were significant predictors of block phase performance but that their directions of application were not. Furthermore, GRF magnitudes which were greater throughout the entire push phase against each block, not just higher peak force magnitudes, were associated with higher levels of performance. A greater rear block force magnitude from the very onset was the most important predictor, and it may also be beneficial to push for a slightly longer proportion of the total block phase with the rear leg. A greater front block force magnitude throughout the majority of the block phase was also identified as an important predictor, as well as ensuring that a forceful push is sustained with the front leg during the early-mid part of the block phase around the time when the rear foot is generating its peak forces. Practitioners are encouraged, where possible, to qualitatively assess the magnitude of the force time-histories against each block throughout the entire block phase in addition to discrete values in order to assess the above information and more completely understand external block phase kinetics. Where force data are not directly available, practitioners should be encouraged to determine the average resultant force and its direction (e.g. from horizontal and vertical exit velocities and push phase durations obtained from video images) as summary representations of the force characteristics which could be used to assess overall changes in block phase force magnitude or direction of force application.

References

Baumann, W. (1976). Kinematic and dynamic characteristics of the sprint start. In P. V. Komi (Ed.), Biomechanics V-B (pp. 194-199). Baltimore, MD: University Park Press.

Bezodis, N. E, Salo, A. I. T, & Trewartha, G. (2010). Choice of sprint start performance measure affects the performance-based ranking within a group of sprinters: which is the most appropriate measure? *Sports Biomechanics*, *9*(4), 258-269.

Bezodis, N. E., Salo, A. I. T., & Trewartha, G. (2015). Relationships between lower-limb kinematics and block phase performance in a cross section of sprinters. *European Journal of Sport Science*, *15*(2), 118-124.

Brazil, A., Exell, T., Wilson, C., Willwacher, S., Bezodis, I. N., & Irwin, G. (2018). Joint kinetic determinants of starting block performance in athletic sprinting. *Journal of Sports Sciences*, *36*(14), 1656-1662.

Ciacci, S., Merni, F., Bartolomei, S., & Di Michele, R. (2017). Sprint start kinematics during competition in elite and world-class male and female sprinters. *Journal of Sports Sciences*, *35*(13), 1270-1278.

Čoh, M., Peharec, S., & Bacic, P. (2007). The sprint start: biomechanical analysis of kinematic, dynamic and electromyographic parameters. *New Studies in Athletics, 22*(3), 29-38.

Čoh, M., Peharec, S., Bacic, P., & Mackala, K. (2017). Biomechanical differences in the sprint start between faster and slower high-level sprinters. *Journal of Human Kinetics*, *56*(1), 29-38.

Fortier, S., Basset, F. A., Mbourou, G. A., Faverial, J., & Teasdale, N. (2005). Starting block performance in sprinters: A statistical method for identifying discriminative parameters of the performance and an analysis of the effect of providing feedback over a 6-week period. *Journal of Sports Science and Medicine*, *4*(2), 134-143.

Guissard, N., & Duchateau, J. (1990). Electromyography of the sprint start. *Journal of Human Movement Studies*, *18*(3), 97-106.

Guissard, N., Duchateau, J., & Hainaut, K. (1992). EMG and mechanical changes during sprint starts at different front block obliquities. *Medicine and Science in Sports and Exercise*, *24*(11), 1257-1263.

Gutiérrez-Dávila, M., Dapena, J., & Campos, J. (2006). The effect of muscular pre-tensing on the sprint start. *Journal of Applied Biomechanics, 22*(3), 194-201.

Hafez, A. M. A., Roberts, E. M., & Seireg, A. A. (1985). Force and velocity during front foot contact in the sprint start. In D. A. Winter, R. W. Norman, R. P. Wells, K. C. Hayes, & A. E. Patla (Eds.), *Biomechanics IX-B* (pp. 350-355). Champaign, IL: Human Kinetics.

Mero, A., Luhtanen, P., & Komi, P. V. (1983). A biomechanical study of the sprint start. *Scandinavian Journal of Sports Science, 5*(1), 20-28.

Mero, A., Kuitunen, S., Harland, M., Kyröläinen, H., & Komi, P. V. (2006). Effects of muscle-tendon length on joint moment and power during sprint starts. *Journal of Sports Sciences*, *24*(2), 165-173.

Milanese, C., Bertucco, M., & Zancanaro, C. (2014). The effects of three different rear knee angles on kinematics in the sprint start. *Biology of Sport*, *31*(3), 209-215.

Morin, J.-B., Edouard, P., & Samozino, P. (2011). Technical ability of force application as a determinant factor of sprint performance. *Medicine & Science in Sports & Exercise*, *43*(9), 1680-1688.

Otsuka, M., Shim, J. K., Kurihara, T., Yoshioka, S., Nokata, M., & Isaka, T. (2014). Effect of expertise on 3D force application during the starting block phase and subsequent steps in sprint running. *Journal of Applied Biomechanics, 30*(3), 390-400.

Pain, M. T., & Hibbs, A. (2007). Sprint starts and the minimum auditory reaction time. *Journal of Sports Sciences*, *25*(1), 79-86.

Payne, A. H., & Blader, F. B. (1971). The mechanics of the sprint start. In J. Vredenbregt & J. Wartenweiler (Eds.), *Biomechanics II* (pp. 225-231). Baltimore: University Park Press.

Rabita, G., Dorel, S., Slawinski, J., Sàez-de-Villarreal, E., Couturier, A., Samozino, P., & Morin, J.-B. (2015). Sprint mechanics in world-class athletes: a new insight into the limits of human locomotion. *Scandinavian Journal of Medicine & Science in Sports*, *25*(5), 583-594.

Slawinski, J., Bonnefoy, A., Leveque, J. M., Ontanon, G., Riquet, A., Dumas, R., & Cheze, L. (2010). Kinematic and kinetic comparisons of elite and well-trained sprinters during sprint start. *Journal of Strength and Conditioning Research*, *24*(4), 896-905.

Slawinski, J., Dumas, R., Cheze, L., Ontanon, G., Miller, C., & Mazure-Bonnefoy, A. (2012). 3D kinematic of bunched, medium and elongated sprint start. *International Journal of Sports Medicine*, *33*(7), 555-560.

Slawinski, J., Dumas, R., Cheze, L., Ontanon, G., Miller, C., & Mazure-Bonnefoy, A. (2013). Effect of postural changes on 3D joint angular velocity during starting block phase. *Journal of Sports Sciences*, *31*(3), 256-263.

Smith, G. (1989). Padding point extrapolation techniques for the Butterworth digital filter. *Journal of Biomechanics*, *22*(8-9), 967-971.

Smith, A. C., Roberts, J. R., Kong, P. W., & Forrester, S. E. (2017). Comparison of centre of gravity and centre of pressure patterns in the golf swing. *European Journal of Sport Science*, *17*(2), 168-178.

van Coppenolle, H., Delecluse, C., Goris, M., Bohets, W., & Vanden Eynde, E. (1989). Technology and development of speed: evaluation of the start, sprint and body composition of Pavoni, Cooman and Desruelles. *Athletics Coach*, *23*(1), 82-90.

Warmenhoven, J., Cobley, S., Draper, C., Harrison, A., Bargary, N., & Smith, R. (2017). Considerations for the use of functional principal components analysis in sports biomechanics: examples from on-water rowing, *Sports Biomechanics*, DOI: 10.1080/14763141.2017.1392594.

Willwacher, S., Herrmann, V., Heinrich, K., Funken, J., Strutzenberger, G., Goldmann, J. P., … Bruggemann, G. P. (2016). Sprint start kinetics of amputee and non-amputee sprinters. *PLoS One*, *11*(11), e0166219.

Tables

Table 1. Amount of cumulative variance (%) explained by each mode for each signal.

Mode	Rear block RF	Front block RF	Rear block F_R	Front b
1	75.8	74.8	79.4	67
2	83.5	83.9	85.0	78
3	87.9	88.5	88.7	84
4	90.2	91.4	91.3	87
5				91

Table 2. Qualitative interpretation of a one standard deviation increase in the mean mode coefficie

of the four significant predictor modes.

Signal	Mode	Relative contribution (standardised β coefficient)	Qualitative inte
Rear block F_R magnitude	1	1.185	Greater ‘pretension’ force from very sta “set” position), and greater through
Front block F_R magnitude	1	0.791	Relatively minor differences during consistently greater force magnitude
Rear block F_R magnitude	3	0.254	Earlier rise in force towards an earlier decline and a later
Front block F_R magnitude	4	0.224	Later initial rise in force, but to a highe the rear foot is also pushing (i.e. up to ~ and lower peak in,

Figures

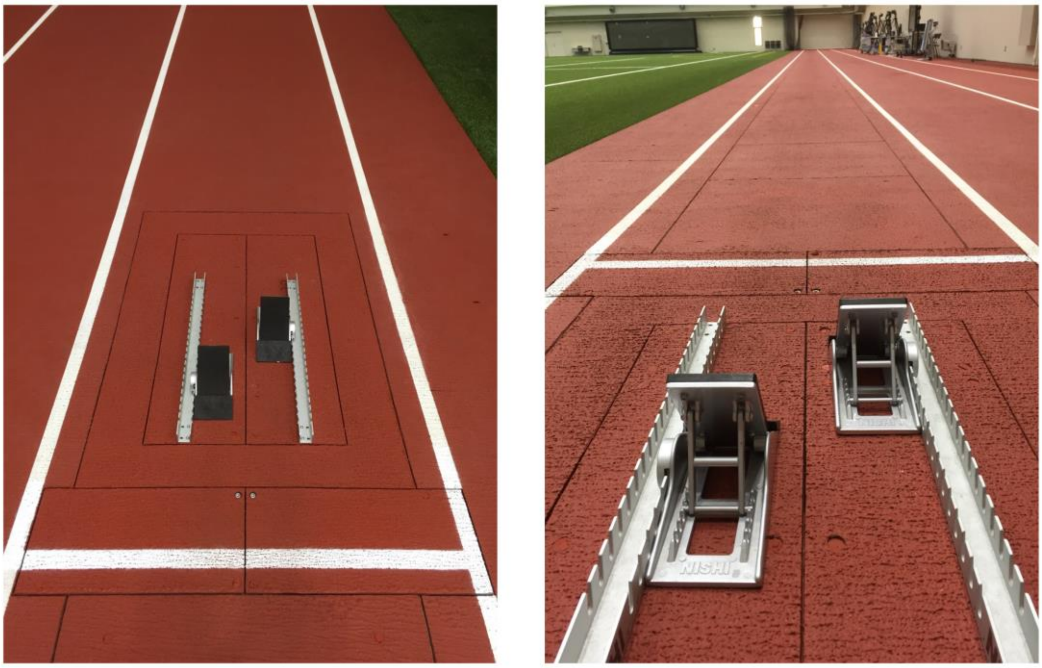

Figure 1. Depiction of the experimental set-up including force platform locations for each of the four points of ground contact.

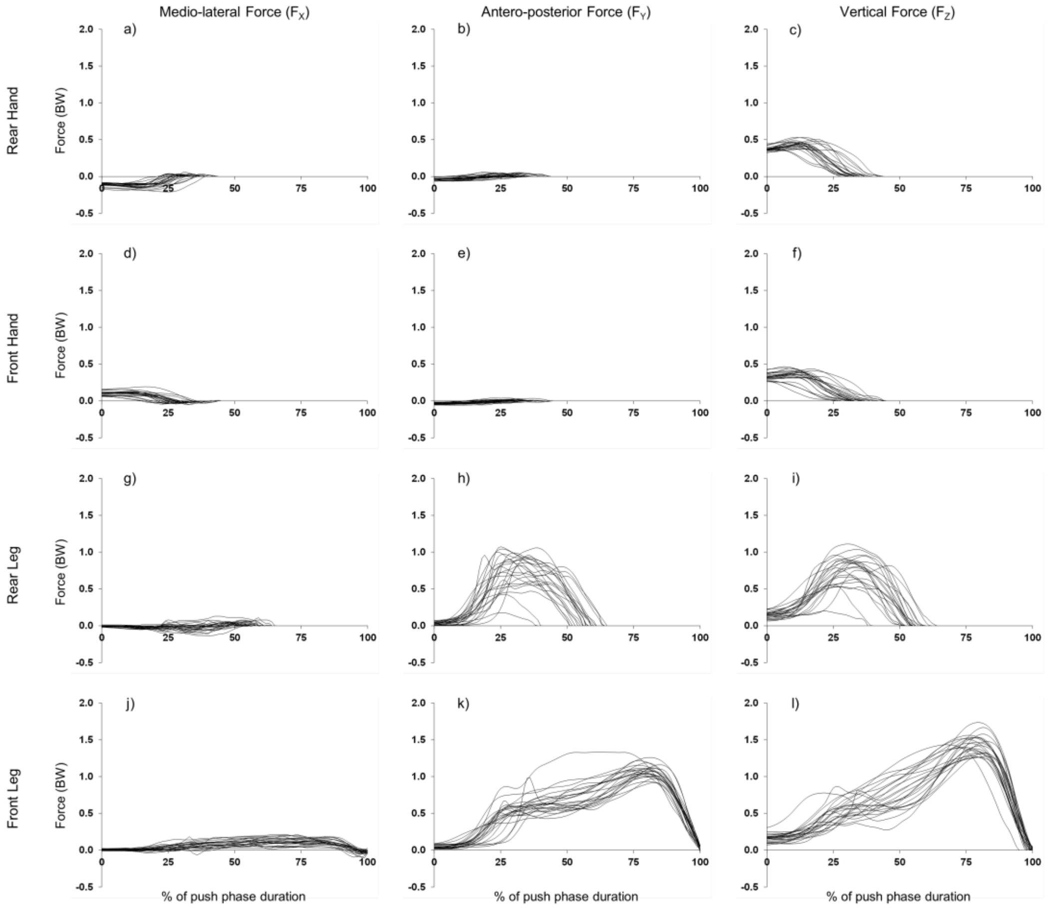

Figure 2. Medio-lateral (F_X), antero-posterior (F_Y) and vertical (F_Z) forces at each of the four points of contact (i.e. both hands and front and rear block) for each of the 23 individual sprinters' best trials, expressed as a percentage of total push phase duration (i.e. from movement onset to front block exit).

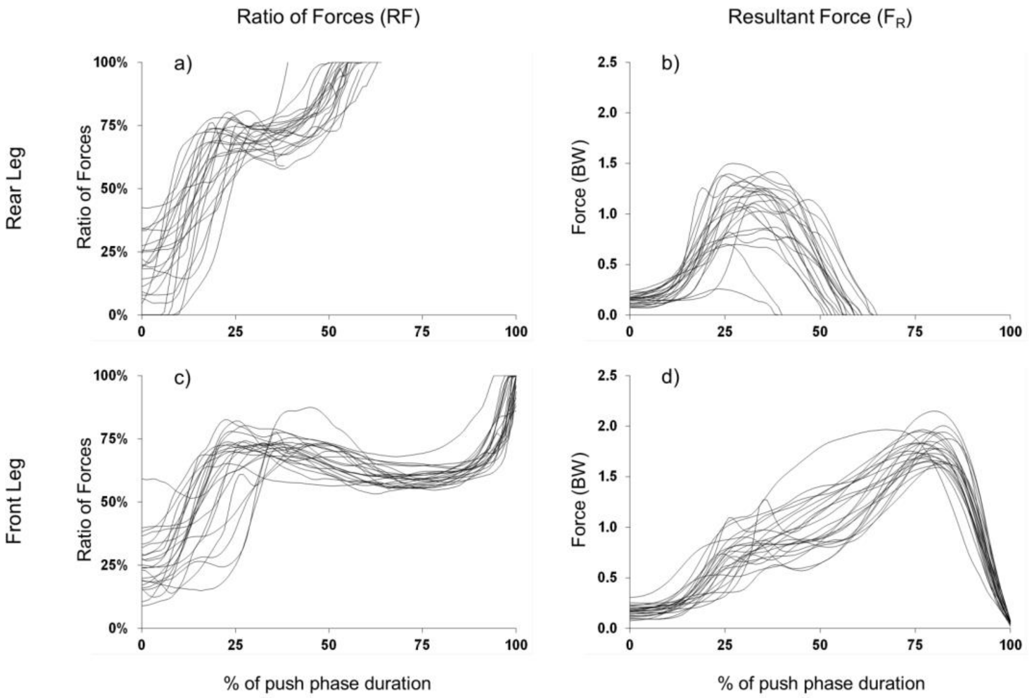

Figure 3. Resultant force (F_R) and ratio of forces (RF) at each of the two blocks for each of the 23 individual sprinters' best trials, expressed as a percentage of total push phase duration (i.e. from movement onset to front block exit). These were the four signals input to the functional data analysis (the final value of the rear foot RF signal was replicated from rear block exit to front block exit prior to inclusion in the functional data analysis).

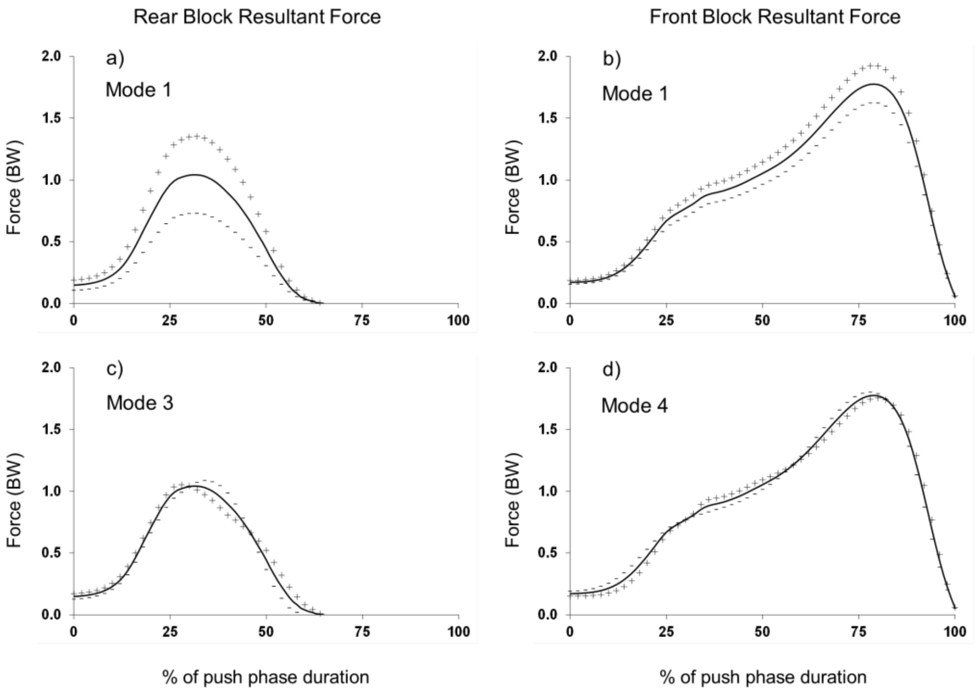

Figure 4. The effects of a one standard deviation increase (+) and decrease (-) in the mean mode coefficient score on the mean signal (solid line) for each of the significant predictor modes.