LINEARITY OF THE RATIO OF FORCES-VELOCITY RELATIONSHIP IS NOT RELATED TO INITIAL ACCELERATION PERFORMANCE IN SPRINTING

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The relationship between the linearity of the ratio of forces (RF)-horizontal velocity (v_H) profile and initial acceleration (IA) performance was investigated in trained sprinters. Ground reaction force data from the IA phase of a maximal sprint from a block start were analysed. The coefficient of determination of the linear trendline fitted to four step-averaged values of RF and v_H provided a measure of linearity. Semi-partial correlations (sr) accounting for block phase performance revealed a weak negative relationship between linearity of the RF-v_H profile and performance over the first four steps (sr = -0.11), while mean RF displayed a very strong positive relationship with performance (sr = 0.80). Sprinters and coaches should therefore prioritise the production of a high RF during IA above trying to ensure a consistent decline in RF as velocity increases.

KEYWORDS: ground reaction forces, sprint start, sprint, technical ability, track and field.

INTRODUCTION: An athlete's ability to accelerate effectively can be a determining factor for success in many sports. The initial acceleration (IA) phase of maximal sprinting, defined as the first four steps following block exit (Nagahara et al., 2014), is when the largest forward accelerations are observed (Nagahara et al., 2020). Therefore, the IA phase has been the subject of considerable research to understand the principles underpinning high performance. A key element of high sprint acceleration performance is effective orientation of force output (Morin et al., 2011; Rabita et al., 2015). This 'technical ability' is typically measured by the ratio of forces (RF), which describes the proportion of the step-averaged resultant force vector (F_R) that is directed horizontally (F_H), i.e. RF = F_H/F_R (Morin et al., 2011). When quantifying technical ability over all, or any part, of the acceleration phase, a linear trendline is often fitted to step-averaged RF with respect to step-averaged horizontal velocity (v_H), denoted as the RF-v_H profile. The gradient of this trendline quantifies the ability to maintain RF as v_H increases, termed rate of decline in RF (D_{RF}; Morin et al., 2011). The y-intercept provides the theoretical maximal RF at null velocity, termed RF_0 (Rabita et al., 2015), whilst other measures such as RF_{MAX} (RF value at 0.3 s; Samozino et al., 2016) are also sometimes extracted.

These measures of technical ability have shown strong relationships with early acceleration (block phase and IA) performance (Bezodis et al., 2020). However, the RF-v_H profile is typically created using data from the entire acceleration phase, which is not always closely related to the RF-v_H profile during early acceleration, as considerable step-to-step variation in RF can be observed, particularly during the IA phase (Bezodis et al., 2020). This variation in RF during the IA phase of the sprint can be quantified from the coefficient of determination (adjusted R^2) of the linear trendline fitted to the RF-v_H profile. Hereafter termed 'linearity', this coefficient allows objective assessment of an athlete's step-to-step variation in the decreasing RF over IA. The aim of this study was to determine the strength of the relationship between the linearity of the RF-v_H profile and performance over the IA phase in trained sprinters.

METHODS: Fourteen male sprinters (mean ± SD: age = 20 ± 1 years; height = 1.73 ± 0.07 m; mass = 68.6 ± 4.9 kg; 100 m personal best = 11.15 ± 0.33 s) gave informed consent to participate in this study which was approved by the local research ethics committee. Participants completed their preferred warm-up routine before performing two maximal sprint efforts to 60 m from starting blocks, while wearing spiked shoes on an indoor track. Participants were provided with a rest period of ≥10 minutes between efforts. Ground reaction force (GRF) data were collected at 1000 Hz from a 52 m series of force plates (TF-3055, TF-32120, TF-90100, Tec Gihan, Uji, Japan), mounted under the track. An electric starting gun was used to synchronously initiate the GRF data collection and emit an auditory starting signal. All data were recorded and analysed in MATLAB (R2021a, Natick, USA).

For all trials, a 50 N threshold in the raw vertical GRF data was used to identify touchdown and toe-off. Movement onset was defined as the first point at which the raw vertical GRF exceeded, and remained, two standard deviations above the mean stationary signal in the blocks (Bezodis et al., 2020). The raw GRF data were filtered using a 4th order low-pass Butterworth filter with a cut-off frequency of 50 Hz. After accounting for the influence of air resistance (Samozino et al., 2016), horizontal velocity (v_H) and displacement were determined using trapezoid integration.

Spatiotemporal variables across steps one to four were calculated. Step-averaged force data from each stance phase were determined from the resultant GRF (F_R) and its vertical (F_V) and antero-posterior (F_H) components. Following this, step-averaged RF was calculated (F_H/F_R) and mean RF from the first four steps was determined (RF_{MEAN}). Mean resultant GRF magnitude ($F_{R\ MEAN}$) was also calculated over these four steps. A linear trendline was fitted through the four step-averaged RF and v_H values, from which D_{RF} and RF_0 were extracted (Rabita et al., 2015). The coefficient of determination (adjusted R^2) of this trendline was also calculated to quantify the linearity of the relationship between RF and v_H across the IA phase. Normalised average horizontal external power (NAHEP) from the beginning of first contact to the end of fourth contact was used as a measure of IA performance (Bezodis et al., 2010).

The trial in which each participant displayed the highest NAHEP was used for all subsequent analyses, with the exception of one trial in which the participant was clearly not stationary prior to movement onset. A semi-partial correlation coefficient (sr) was calculated between NAHEP and each of the associated kinetic measures ($F_{R\ MEAN}$, RF_{MEAN}, RF_0, D_{RF}, linearity of the RF-v_H fit), accounting for v_H at first touchdown which quantified performance up to that instant. A repeated measures ANOVA was used to assess differences in all variables between steps over the IA phase. Correlation thresholds were defined according to Batterham & Hopkins (2006) as trivial (0.0), small (0.1), moderate (0.3), large (0.5), very large (0.7), nearly perfect (0.9) and perfect (1.0). Statistical significance was accepted at $p < 0.05$.

RESULTS AND DISCUSSION: The repeated measures ANOVA revealed significant main effects for all variables over the IA phase (Table 1). All of the spatiotemporal variables progressively increased from steps 1 to 4, except contact time which decreased. Regarding the kinetics, average F_R magnitude increased over IA and the average F_H component progressively decreased. RF therefore decreased across the IA phase whilst v_H progressively increased. The IA performance defined by AHEP and NAHEP was 1779 ± 177 W and 0.65 ± 0.05, respectively.

Table 1. Step-to-step spatiotemporal, GRF-derived, and overall acceleration performance measures (all mean ± SD) over the IA phase.

Measure	Units	Step 1	Step 2	Step 3	Step 4
Velocity at end of contact **	(ms^{-1})	4.41 ± 0.20	5.27 ± 0.22	5.97 ± 0.21	6.57 ± 0.21
Time to end of contact^ **	(s)	0.637 ± 0.025	0.861 ± 0.036	1.083 ± 0.047	1.301 ± 0.060
Displacement at end of contact^ **	(m)	1.52 ± 0.11	2.57 ± 0.21	3.78 ± 0.30	5.11 ± 0.42
Contact time **	(s)	0.190 ± 0.016	0.164 ± 0.018	0.149 ± 0.017	0.134 ± 0.011
Flight time[†] *	(s)	0.060 ± 0.020	0.073 ± 0.016	0.085 ± 0.018	0.092 ± 0.013
Step length[§] **	(m)	1.10 ± 0.12	1.24 ± 0.11	1.36 ± 0.12	1.47 ± 0.11
Step frequency *	($steps.s^{-1}$)	4.02 ± 0.30	4.24 ± 0.28	4.31 ± 0.38	4.45 ± 0.22
Average F_R magnitude *	(BW)	1.47 ± 0.14	1.50 ± 0.16	1.67 ± 0.16	1.74 ± 0.14
Average F_H component *	(BW)	0.61 ± 0.06	0.54 ± 0.06	0.48 ± 0.07	0.45 ± 0.05
Step-averaged RF *	(%)	41.83 ± 1.66	36.66 ± 2.87	29.75 ± 3.20	26.93 ± 2.26
Step-averaged v_H **	(ms^{-1})	3.74 ± 0.18	4.76 ± 0.20	5.53 ± 0.21	6.18 ± 0.21

^Relative to movement onset. [†]Following contact phase. [§]Touchdown to next touchdown. *Significant main effect of step ($p < 0.05$); variables marked ** exhibited pairwise differences between all four steps when assessed using a Bonferroni correction.

A very large, significant relationship (sr = 0.80) was observed between RF_{MEAN} and IA performance (Table 2). These findings support Bezodis et al. (2020), who found a very large correlation (r = 0.88) between early acceleration performance (NAHEP) and RF_{MEAN} over this period. The moderate correlation between $F_{R\ MEAN}$ and performance over initial acceleration (sr = 0.33) also supports the findings of Bezodis et al. (2020) with RF being of greater importance for IA performance than resultant GRF magnitude.

Table 2. GRF-derived and technical ability measures (Mean ± SD) extracted from the RF-v_H fit over the IA phase and semi-partial correlations (sr) with NAHEP over the IA phase.

Measure	Units	Mean over 4 steps (IA phase)	Semi-partial correlation (sr)
$F_{R\ MEAN}$	(BW)	1.60 ± 0.13	0.333
RF_{MEAN}	(%)	33.79 ± 1.57	0.795*
RF_0	(%)	66.06 ± 5.47	-0.276
D_{RF}	(%·s/m)	-6.37 ± 1.15	0.474
Linearity of RF-v_H fit (R^2)		0.870 ± 0.130	-0.105

*Correlation is significant ($p < 0.05$)

Although Bezodis et al. (2020) also included the block phase as well as the first four steps in their analysis, the aforementioned findings of the current study are comparable as the semi-partial correlation with IA performance accounted for block phase performance. However, this discrepancy in phase definition appears to have impacted the comparison in relationships between the RF-v_H profile-derived measures and performance. While Bezodis et al. (2020) found a strong relationship for RF_0 (r = 0.59) and no relationship for D_{RF} (r = -0.04), the current study found a weak negative relationship for RF_0 (sr = -0.28) and a moderate relationship for D_{RF} (sr = 0.47). These conflicting findings suggest that the inclusion of block phase RF and v_H values may alter these relationships, although this could also be due to differences in the studied participants and thus future work should directly investigate this.

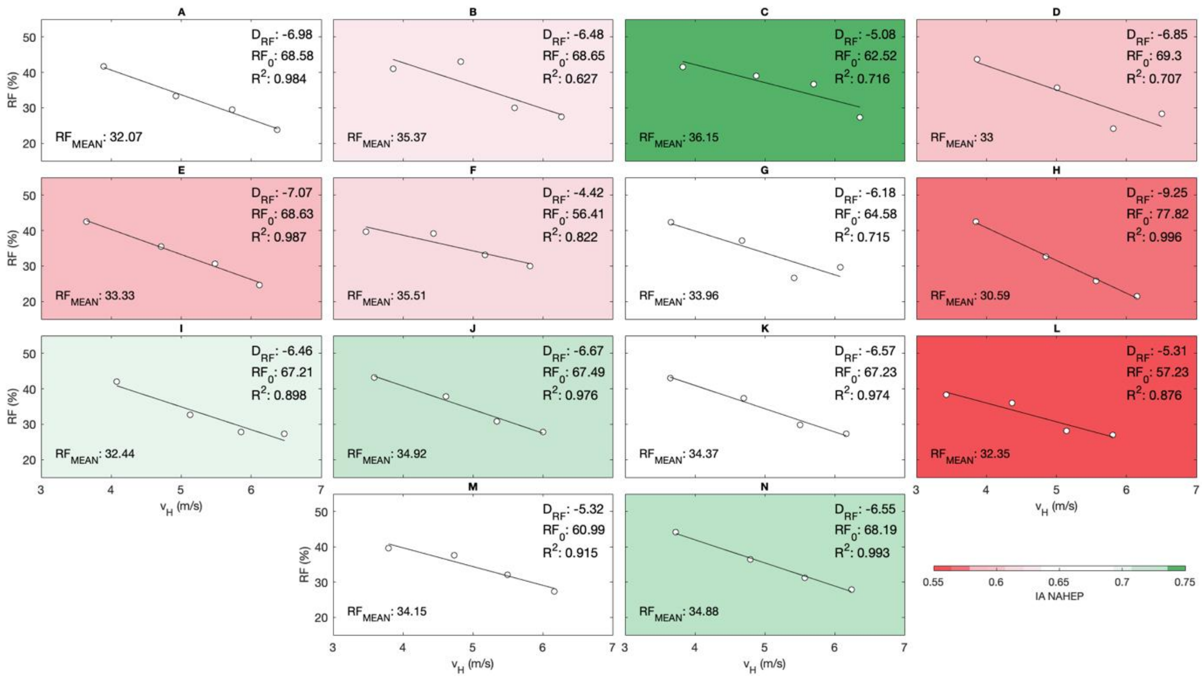

Figure 1. RF-v_H profiles for all 14 sprinters (A-N) across the IA phase with individual linear trendlines fitted through all four steps. Technical ability descriptors based on the slope (D_{RF}) and y-intercept (RF_0) of this trendline, and the goodness of fit (R^2), for each individual are stated in the top right of each plot, while RF_{MEAN} over IA is stated in the bottom left. Plot backgrounds are colour coded according to IA performance (NAHEP) from lowest (red) to highest (green) – see colour scale in bottom right of figure.

RF-v_H profiles throughout the IA phase varied considerably between individuals (Figure 1). The highest IA performance was achieved by Participant C (NAHEP = 0.750, most green background), whilst the lowest performance was achieved by Participant L (NAHEP = 0.563, most red background). Three common patterns in RF-v_H profiles were observed for the participants. Firstly, participants B, F, L & M, typically produced higher RF on step 2 aside from their mostly linear RF-v_H relationship over IA (R^2 range = 0.63-0.92; Figure 1). Secondly, participants D, G, I, J & K, produced lower RF on their third step before an increase in step 4 (R^2 range = 0.71-0.90; Figure 1). Lastly, participants A, E, H & N all showed a largely linear RF-v_H relationship over IA phase (all $R^2 \geq 0.98$) (Figure 1). While participant C achieved the highest performance, their RF-v_H profile was different from the other participants – a linear relationship for the first three steps followed by a notable decrease in RF on step 4 ($R^2 = 0.72$). The relationship between linearity of the RF-v_H fit and performance was small and negative (sr = -0.11) (Table 2). These findings suggest that high acceleration performance can be achieved regardless of any step-to-step variation in RF. This is particularly evident from the RF-v_H profile of participant C, who achieved the highest IA NAHEP value (0.75) while displaying one of the least linear profiles of the cohort ($R^2 = 0.72$) (Figure 1).
Future research targeted on understanding the kinematic features which underpin the ability to achieve a high RF during IA can therefore confidently focus on RF_{MEAN} over the period of interest rather than needing to consider step-to-step variation, although features which relate to this variation in RF may be worthy of future exploration. Furthermore, future research investigating technical performance during acceleration can confidently used the outputs from a simple macroscopic model (Samozino et al., 2016) as it is the average RF characteristics during IA which relate to performance, whereas the magnitude of individual step-to-step variation which is neglected by the model does not relate to IA performance.

CONCLUSION: There was a weak negative relationship between the linearity of the RF-v_H profile and performance over the first four steps, whereas mean RF over these steps displayed a very strong positive relationship with performance. As mean RF over the initial acceleration phase appears to be the only significant predictor of performance, sprinters and coaches should prioritise the production of a high RF over the whole initial acceleration phase above trying to ensure a consistent decline in RF as velocity increases.

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