UNDERSTANDING RATIO OF FORCES DURING EARLY ACCELERATION

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Ratio of forces (RF) were investigated during early acceleration by analysing block and standing starts in trained sprinters. RF variables over the initial block exit/push-off and the first four steps were determined from force plate data, and a simple macroscopic model was also applied to obtain RF variables from the velocity time-history over the entire acceleration phase. Large positive correlations existed between mean early acceleration RF and early acceleration performance from both standing (r = 0.82) and block (r = 0.89) starts, and both theoretical maximal RF and the rate of decline in RF combined to be important predictors (adj. R^2 = 92-97%) of performance. From the simple macroscopic model, maximum RF was nearly perfectly correlated with early acceleration performance (r = 0.96) and thus appears to be an excellent simple measure for early acceleration.

KEY WORDS: ground reaction forces, sprint start, sprinting, team sports, track and field.

INTRODUCTION: The ability to rapidly accelerate from stationary is a fundamental requirement for track sprinters and team sport athletes. The techniques used during the start of the acceleration phase (hereafter termed 'early acceleration') are therefore often scrutinised closely by coaches in an attempt to improve performance. It is well established that an athlete's "technical" ability to direct the ground reaction forces (GRFs) more horizontally (i.e. a higher ratio of forces (RF); Morin, Edouard, & Samozino, 2011) is an important feature for their overall acceleration performance (Morin et al., 2011; Rabita et al., 2015). These RF measures are typically determined from data obtained over an entire acceleration phase (e.g. Morin et al., 2011; Rabita et al., 2015; Samozino et al., 2016). A linear trendline is typically fitted to RF with respect to horizontal velocity (v_H) and the rate of decline (D_{RF}; Morin et al., 2011) is often extracted as an indicator of force application technique. Other RF measures during early acceleration have also been extracted, including some which are intended to quantify an athlete's maximal RF abilities such as the theoretical maximal RF at null velocity from the linear RF-v_H fit (RF_0; Rabita et al., 2015), the maximal step-averaged RF (Morin et al., 2011), and the RF value at 0.3 s based on a linear fit to RF-v_H from 0.3 s onwards (RF_{MAX}; Samozino et al., 2016). Further measures intended to quantify RF during early acceleration include mean RF (RF_{MEAN}) up to specific distances (e.g. 10 m; Samozino, 2018) or over specific durations (e.g. 2 s, Bayne, 2018; 4 s, Morin et al., 2011).

Whilst measures of maximal or average RF ability are intended to provide a measure which is more specific to early acceleration, they are frequently determined from a linear function fitted to the RF-v_H data from the first step until the maximal velocity plateau. It therefore remains unknown whether these measures provide an appropriate representation of an athlete's RF abilities during early acceleration, or whether they may be biased by an athlete's abilities later in the acceleration phase (Samozino, 2018) and thus a more specific fit to the early acceleration data may provide a more appropriate representation.

The first aim of the current study was to investigate the association between directly measured RF_{MEAN} during early acceleration and a direct measure of performance over the same period (i.e. the initial push-off and first four steps). The second aim was then to explore the relative importance of D_{RF} and RF_0 in achieving RF_{MEAN}. Both of the above aims included separate consideration of starts from standing and blocks in order to determine whether the type of start used could affect these associations. The final aim was to assess the relationship between the D_{RF} and RF_{MAX} outputs obtained from a simple macroscopic model fitted to the v_H-time data over the entire acceleration phase (Samozino et al., 2016) against the force plate determined RF and performance variables during early acceleration.

METHODS: Twenty-four male sprinters (mean ± SD: age = 20 ± 1 years; height = 1.73 ± 0.06 m; mass = 65.7 ± 4.0 kg; 100 m PB = 11.26 ± 0.39 s) who were experienced with block and standing starts provided 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. Following a self-directed warm-up, all sprinters performed four maximal effort 60 m sprints whilst wearing spiked shoes: two from a block start and two from a two-point standing start in a relatively crouched posture. The order of conditions was randomised and a rest period of ≥10 minutes was provided between sprints. All sprints took place on an indoor track over a 52 m series of force plates (TF-3055, TF-32120, TF-90100, Tec Gihan, Uji, Japan) which recorded GRF data at 1000 Hz. An electric starting gun was used to synchronously initiate the GRF data collection and emit an auditory starting signal. All recorded GRF data were exported for analysis in Matlab (R2015a, Natick, USA).

Based upon an initial visual inspection of the data, 10 standing start trials were removed from the analysis because the sprinter was clearly not stationary immediately after the starting signal. For all trials, movement onset was determined from the raw antero-posterior GRFs as the first sample which increased above, and remained above for more than 0.1 s, two standard deviations above the mean raw antero-posterior force during the first ~0.05 s of the trial. The vertical and antero-posterior GRF data were filtered using a 4^{th} order low-pass Butterworth filter with a cut-off frequency of 70 Hz. Each toe-off (or block exit for the first event of the block start trials) and touchdown was identified using a 20 N threshold in the filtered vertical GRF data. Horizontal velocity was determined from the antero-posterior GRFs using the impulse-momentum relationship accounting for the influence of air resistance (Samozino et al., 2016; Colyer, Nagahara, & Salo, 2018). Step-averaged values of horizontal velocity, horizontal GRF and vertical GRF were determined from each contact and subsequent flight phase (including for the initial block exit/push-off step), and these step-averaged force values were used to determine the step-averaged RF (Morin et al., 2011).

For the purposes of this study, early acceleration was the initial block exit/push-off step and the first four steps on the track. Mean RF ($RF_{MEAN\text{-}FP}$) was calculated from the five step-averaged RF values, and a linear trendline was fitted through the five RF and v_H values. The gradient was extracted as a modelled measure of the rate of decline in RF ($D_{RF\text{-}FP}$), with the y-intercept extracted as a measure of theoretical maximal RF ($RF_{0\text{-}FP}$). Early acceleration performance was quantified by extracting the velocity of the sprinter at the 4^{th} step toe-off and the time taken to reach this toe-off (relative to the instant of movement onset). These values were then used to determine the normalised average horizontal external power (NAHEP) produced by the sprinter over the entire period from movement onset to 4^{th} step toe-off following the procedures outlined by Bezodis, Salo and Trewartha (2010).

The force plate determined v_H-time data from movement onset to toe-off of the step with the highest stance-averaged velocity were then fitted with a mono-exponential function to obtain a simple macroscopic model (Samozino et al., 2016). The modelled horizontal force-time data were determined based on these fitted velocity data and the modelled effects of drag. Vertical force was assumed to be equal to body weight throughout. The instantaneous RF time-history throughout the sprint was then determined (Morin et al., 2011). Based on the procedures of Samozino et al. (2016), the value of this RF function at 0.3 s was extracted ($RF_{MAX\text{-}M}$). A linear function was fitted to the modelled RF-v_H data (ignoring the first 0.3 s of data after movement onset) and the gradient of this function was extracted ($D_{RF\text{-}M}$).

Mean values for each sprinter in each condition were used for all subsequent analyses. Bivariate correlations between the force plate determined RF variables during early acceleration ($RF_{MEAN\text{-}FP}$, $RF_{0\text{-}FP}$, $D_{RF\text{-}FP}$) and the simple macroscopic model variables over the whole acceleration phase ($RF_{MAX\text{-}M}$, $D_{RF\text{-}M}$) were performed, as were their correlations with NAHEP. Stepwise linear regressions were used to determine the combined predictor effects on NAHEP. Correlation thresholds were defined according to 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).

RESULTS: The mean ± SD NAHEP at the end of the fourth contact was 0.565 ± 0.041 (block) and 0.499 ± 0.061 (standing). These were associated with mean ± SD velocities at the end of the fourth contact of 6.51 ± 0.20 m/s (block) and 6.55 ± 0.36 m/s (standing), and times of 1.28 ± 0.07 s (block) and 1.47 ± 0.07 s (standing) to the end of the fourth contact. Correlations between the RF measures and early acceleration performance (NAHEP over the block exit/push-off and the first four steps) are presented in Table 1.

Table 1. Pearson's correlations (r, (90% confidence limits)) between RF measures and early acceleration performance (NAHEP over the block exit/push-off and the first four steps).

	Measure	Blocks	Standing
Measured and modelled from force plates during push-off and first four steps	$RF_{MEAN-FP}$	0.89 (0.79 : 0.94)	0.82 (0.66 : 0.91)
	RF_{0-FP}	0.62 (0.35 : 0.79)	0.68 (0.43 : 0.83)
	D_{RF-FP}	-0.10 (-0.43 : 0.25)	-0.14 (-0.47 : 0.22)
Simple macroscopic model over entire acceleration phase	RF_{MAX-M}	0.96 (0.92 : 0.98)	0.96 (0.92 : 0.98)
	D_{RF-M}	-0.48 (-0.71 : -0.16)	-0.70 (-0.84 : -0.46)

The stepwise linear regression revealed that RF_{0-FP} and D_{RF-FP} explained 92% (block) and 97% (standing) of the variance (i.e. adjusted R^2) in NAHEP. The standardised beta-coefficients were 1.73 (RF_{0-FP}) and 1.34 (D_{RF-FP}) from the blocks, and 1.68 (RF_{0-FP}) and 1.23 (D_{RF-FP}) from standing. For the simple macroscopic model over the entire acceleration phase, RF_{MAX-M} and D_{RF-M} explained 95% (block) and 96% (standing) of the variance in NAHEP. The standardised beta-coefficients were 1.13 (RF_{MAX-M}) and 0.26 (D_{RF-M}) from the blocks and 1.26 (RF_{MAX-M}) and 0.35 (D_{RF-M}) from standing. Correlations between the force plate determined and simple macroscopic model RF variables are presented in Table 2.

Table 2. Pearson's correlations (r, (90% confidence limits)) between force plate determined and simple macroscopic model RF variables for block and standing starts.

Blocks		Simple macroscopic model		**Standing**		Simple macroscopic model	
		RF_{MAX-M}	D_{RF-M}			RF_{MAX-M}	D_{RF-M}
Force plate determined	$RF_{MEAN-FP}$	0.81 (0.65 : 0.90)	-0.36 (-0.63 : -0.02)	Force plate determined	$RF_{MEAN-FP}$	0.69 (0.45 : 0.84)	-0.35 (-0.63 : 0.00)
	RF_{0-FP}	0.74 (0.53 : 0.86)	-0.67 (-0.82 : -0.42)		RF_{0-FP}	0.80 (0.62 : 0.90)	-0.86 (-0.93 : -0.73)
	D_{RF-FP}	-0.26 (-0.55 : 0.09)	0.53 (0.23 : 0.74)		D_{RF-FP}	-0.33 (-0.61 : 0.02)	0.64 (0.37 : 0.81)

DISCUSSION: A very large, positive relationship was observed between directly measured $RF_{MEAN-FP}$ and NAHEP during early acceleration (Table 1). This supports previous evidence from the entire acceleration phase regarding the importance of RF (Morin et al., 2011; Rabita et al., 2015) and extends it to a specific early part of the acceleration phase. When exploring the contributing roles of D_{RF} and RF_0, RF_{0-FP} was more strongly related to NAHEP than D_{RF-FP} based on simple bivariate correlation. However, in a stepwise multiple linear regression, they combined to explain 92-97% of the variance in NAHEP, and the relative importance of RF_{0-FP} was only ~1.3 times greater than D_{RF-FP}. These findings align well with Bayne (2018) who observed large differences in mean modelled RF over the first 2 s between elite and sub-elite sprinters, and moderate and small differences for modelled RF_{MAX} and modelled D_{RF}, respectively. Although there may be a slightly greater importance associated with exhibiting a higher initial RF for early acceleration performance, reducing the rate of decline in RF over this early part of a sprint also appears to interact and play an important role.

For all RF measures from the force plate, all correlations with NAHEP were in the same threshold boundary (according to Hopkins' (2006) convention) between the block and standing starts (Table 1). The type of start used therefore does not appear to have a major effect on the relationships between RF and performance during early acceleration. However, when using the simple macroscopic model, there was a greater effect of the different start types on the relationship between D_{RF-M} and NAHEP (Table 1), and there were also some small differences between the two start types in the correlation coefficients between the force plate determined and simple macroscopic model RF variables (Table 2). Because of the importance of objectively analysing the force plate data in this study, first movement onset was estimated consistently across both start types. Whilst this was likely appropriate for block starts, it may lead to bias in the estimation of RF during standing starts because, based on the GRF profiles, some sprinters appeared to undertake a gradual repositioning of their body prior to their maximal effort push-off. Future work should consider how movement onset identification affects the direct and modelled determination of RF measures.

When assessing the relationship between RF measures from the simple macroscopic model (determined from the entire acceleration phase) and the force plate (determined from the inital block exit/push-off and first four steps), there were very large, positive correlations between RF_{0-FP} and RF_{MAX-M}, large and very large positive correlations between $RF_{MEAN-FP}$ and RF_{MAX-M}, and large positive correlations between D_{RF-FP} and D_{RF-M} (Table 2). Whilst this suggests that the RF profile during early acceleration is closely but not necessarily strongly related to the RF profile over the whole acceleration phase, the relationships between the simple macroscopic model measures and performance revealed nearly perfect correlations between RF_{MAX-M} and early acceleration performance (both r = 0.96; Table 1). The simple macroscopic model RF_{MAX} appears to provide an excellent indicator of early acceleration performance. The force plate determined measures may be more influenced by step-to-step variation during early acceleration, or the linear fit currently applied to them may be too simplistic as the macroscopic model RF_{MAX} is obtained from the mono-exponential RF-v_H function which deviates from the linear fit at these low velocities, and future work is required to explore this further. These relationships have also only been investigated across a cross-section of sprinters and future work should also consider the within-individual effects.

CONCLUSION: A very large positive relationship between mean RF and performance during early acceleration was observed from both block and standing starts. D_{RF-FP} and RF_{0-FP} combined to explain 92-97% of the variance in early acceleration performance. There were some differences in the relationships with performance between RF measures determined directly from the force plates and those obtained via a simple macroscopic model fitted to the v_H-time data over the entire acceleration phase. The RF_{MAX} value from the simple macroscopic model had a nearly perfect correlation with early acceleration performance.

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