ORIGINAL ARTICLE

A comparison between the force–velocity relationships of unloaded and sled-resisted sprinting: single vs. multiple trial methods

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Abstract

Purpose We sought to compare force–velocity relationships developed from unloaded sprinting acceleration to that compiled from multiple sled-resisted sprints.

Methods Twenty-seven mixed-code athletes performed six to seven maximal sprints, unloaded and towing a sled (20–120% of body-mass), while measured using a sports radar. Two methods were used to draw force–velocity relationships for each athlete: A multiple trial method compiling kinetic data using pre-determined friction coefficients and aerodynamic drag at maximum velocity from each sprint; and a validated single trial method plotting external force due to acceleration and aerodynamic drag and velocity throughout an acceleration phase of an unloaded sprint (only). Maximal theoretical force, velocity and power were determined from each force–velocity relationship and compared using regression analysis and absolute bias ($\pm$ 90% confidence intervals), Pearson correlations and typical error of the estimate (TEE).

Results The average bias between the methods was between -6.4 and -0.4%. Power and maximal force showed strong correlations ($r = 0.71$ to 0.86), but large error (TEE $= 0.53$ to 0.71). Theoretical maximal velocity was nearly identical between the methods ($r = 0.99$), with little bias (-0.04 to 0.00 m s^{-1}) and error (TEE $= 0.12$).

Conclusions When horizontal force or power output is considered for a given speed, resisted sprinting is similar to its associated phase during an unloaded sprint acceleration [e.g. first steps (~ 3 m s^{-1}) $=$ heavy resistance]. Error associated with increasing loading could be resultant of error, fatigue, or technique, and more research is needed. This research provides a basis for simplified assessment of optimal loading from a single unloaded sprint.

Keywords Explosive performance · Sprint · Power development · Resisted sprinting

Abbreviations

α	Acceleration
BM	Body mass
ES	Cohen's effect size
F	Horizontal force
F_{aero}	Aerodynamic friction force
F_f	Friction force
F_n	Normal force
F_{opt}	Optimal horizontal force
F_{peak}	Horizontal force at maximum velocity
Fv	Horizontal force–velocity relationship
F_0	Maximum theoretical horizontal force
h_t	Attachment height of tether to athlete
L_{opt}	Optimal external normal loading
m	System mass
P	Horizontal power
P_{max}	Maximum horizontal power
Pv	Horizontal power–velocity relationship
S_{Fv}	Slope of the linear Fv relationship
TEE	Typical error of estimate
v	Horizontal velocity
v_{max}	Maximum horizontal velocity
v_{opt}	Optimal horizontal velocity
v_0	Maximum theoretical horizontal velocity
θ	Angle of pull
μ_k	Coefficient of friction

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Introduction

The assessment of athletic power production is common in sports science practice (Cross et al. 2017b; Jaric 2015). Quantifying the metrics that underlie power production provides insight into the conditions under which training may be oriented (Morin and Samozino 2016); be it for maximal power (Cormie et al. 2007; Wilson et al. 1993), the development of a particular capacity determined as lacking in the athlete (Morin and Samozino 2016), or indeed any other capacity linked to context-specific performance. This information can improve individualised training prescription, resulting in more specific and potentially enhanced adaptations. While these concepts are well acknowledged within wider strength and conditioning and research practice (Scott et al. 2016), the commentary on this topic pertaining to resisted sprint running ('sprinting') is comparatively unclear, owing largely to a current lack of empirical evidence pertaining to loading prescription parameters and their training effects.

Further than simply assessing power production during a given explosive movement, we can gain insight into athlete capabilities by measuring the expression of force production at a range of velocities [i.e. the force–velocity (Fv) relationship] (Morin and Samozino 2016). In practice, Fv relationships are typically assessed using one of two methods: Repeated trials against several conditions of increasing external resistance (i.e. multiple trial method), or during a single trial of cyclic acceleration (i.e. single trial method) (Cross et al. 2017b). Both methods have been shown to provide inverse-linear relationships between force and velocity qualities, and associated parabolic power–velocity (Pv) relationships, as a function of either external resistance or acceleration (multiple and single trial methods, respectively) (Cross et al. 2017b; Jaric 2016). Not only have researchers shown that profiling of Fv relationships is possible during sprinting on treadmills using both multiple (Jaskólska et al. 1998) and single trial approaches (Morin et al. 2010), but that both approaches are possible during overground sprinting (Cross et al. 2017a; Samozino et al. 2016). The ability to apply a single trial method to overground 'free-sprinting' acceleration is particularly valuable, as it provides an accurate and valid (Samozino et al. 2016) depiction of the kinetics that are directly translatable into on-field in many sporting codes (e.g. track and field and rugby union). The multiple trial method can similarly be applied to overground sprinting (Cross et al. 2017a), but requires several trials and a range of external horizontal resistance to generate composite mechanical data. While a necessity for external loading and multiple trials results in a longer and more taxing assessment protocol, the use of practically applicable

resistance and loading protocols (e.g. sleds) allows direct insight into potential training parameters. The accurate assessment of training load parameters to be implemented based on sprinting Fv relationships would be of interest, as although suggestions have been made regarding the orientation of training goals based on Fv relationships provided from using a single-trial approach (Morin and Samozino 2016), direct quantification of loading strategies has not been shown from the single sprint method. Outside of the quantification of loading, however, it is currently unknown whether the mechanical capabilities assessed using a multiple sprint and a single sprint method are characteristically similar.

It is generally acknowledged in resistance training theorem that training as a function of the Fv relationship, or its derivatives [e.g. velocity based training (Scott et al. 2016)], provides an effective way of targeting adaptations (Cormie et al. 2011; Morin and Samozino 2016). For example training in the conditions producing maximal power (P_{max}), termed optimal force (F_{opt}) and optimal velocity (v_{opt}) (Cormie et al. 2011), may acutely and longitudinally maximise power (Cormie et al. 2007; Kawamori and Haff 2004; Wilson et al. 1993). While this concept is acknowledged within jumping and cycling literature (Cross et al. 2017b; Jaric 2015; Soriano et al. 2015), it is mostly absent in the literature concerning sprint training. Resisted sprinting (e.g. sled towing) is widely regarded as a means of overloading capacities specific to sprinting acceleration performance (Petrakos et al. 2016), such as horizontal power production (Morin et al. 2012, 2015; Rabita et al. 2015). However, the current body of literature examining the effects of resisted sprinting is somewhat limited, and typically uses relatively light loading regimes (Petrakos et al. 2016). It appears most researchers cap loading parameters based on the premise that training against resistance above a certain magnitude (e.g. > 10% decrement in unloaded velocity) creates dissimilar conditions to unloaded sprinting, which in turn will lead to negative adaptations in technical and performance markers (Alcaraz et al. 2009; Lockie et al. 2003; Spinks et al. 2007). This theory is largely unsubstantiated (Petrakos et al. 2016), and generally misses the underlying concept of training as a function of the Fv relationship; briefly, in the same manner that training in conditions of high velocity may improve velocity capacity, training under significant loading protocols may have a place in the development of high force or early acceleration capabilities (Morin et al. 2017).

External sled-loading of up to 96% (~ 50% decrement in maximum velocity) of body-mass (BM) has been shown to correspond with acutely maximised power (the 'middle' of the Fv relationship), indicating popularised loading parameters may represent velocity dominant stimuli (Cross et al. 2017a). Notably, in this example 'force-dominant' loading would represent > 96% BM for some athletes (Cross et al.

2017a) [depending on surface (Cross et al. 2017c)]. While there is some pilot evidence to show that training using loads of these magnitudes may result in specific adaptations to the acceleration phase of sprinting (Morin et al. 2017), to the best of our knowledge there has been no research substantiating the acute transfer in mechanical characteristics between unresisted and resisted sprint running. It is therefore difficult to theorise what practical transfer can be expected from training interventions targeted based on the horizontal Fv relationship. Such data would provide a kinetic basis on which to clarify the similarities, or indeed dissimilarities, between a given loaded sprint trial and unloaded sprinting performance, and provide practitioners more information on which to prescribe individualised loading parameters.

The aim of this study was to compare Fv relationships determined via multiple resisted sprints to that determined from a single unloaded sprint trial. More specifically we sought to ascertain whether sprinting with a given load at maximum effort could model the external kinetic conditions experienced during a particular section of an unloaded sprint phase (i.e. corresponding to the same velocity). A secondary aim was to examine whether practical resisted sprint loading parameters could feasibly be determined from a single sprint, negating the need to perform multiple trials.

Methods

Subjects and protocol

The data used for this study were compiled from a pool of male athletes ($n = 27$) assessed to prove the concept of profiling sled sprinting force–velocity–power relationships (Cross et al. 2017b). Consequently, full details regarding these athletes (and the testing procedures in general) can be found in this article. Briefly, athletes were drawn from mixed sporting backgrounds [track and field ($n = 15$), mixed-code recreational ($n = 12$)], training histories and performance levels participated in this study [age 26 ± 5 years; stature 1.8 ± 0.06 m; body-mass 80.0 ± 7.7 kg; maximum sprinting velocity (v_{max}) 8.9 ± 0.79 m s^{-1}; 10 m split time 2.11 ± 0.14 s; and 30 m split time 4.55 ± 0.31 s]. All athletes were uninjured (> 3 months pre-testing), and accustomed with the testing procedures. Athletes could wear whatever footwear they generally perform maximal sprinting efforts in to better replicate maximal performance in all sporting codes tested. Following a detailed warm-up protocol, athletes performed 6 or 7 sprints of towing a sled, loaded with a selection of masses, on a Mondo athletics track. The testing was preceded, and each following trial interceded, with 5 min passive rest. Ethical approval was provided by the Auckland University of Technology Ethics Committee (15/61),

conforming to the Code of Ethics of the World Medical Association (Declaration of Helsinki).

Equipment

To provide resistance, athletes were harnessed (0.34 kg; XLR8, Model: SA1PM, Wellington, NZL; attachment point mid-low back via 3.3 m non-elastic tether) to a heavy-duty sprint sled (5.64 kg; GetStrength, Model: HT 50 mm Sled, Auckland, NZL) loaded with a selection of calibrated plates (Model: PL Comp Discs, Eleiko Sport, Halmstad, SWE). Sprinting performance was measured by a sports radar gun (Model: Stalker ATS II, Applied Concepts, Dallas, TX, USA), attached to a tripod set at 5 m behind the start line and a height of 1 m, collecting outward bound velocity–time data at 46.9 Hz.

Loading selection and sprint distance

Seven resistive parameters (six external loads, and one 'unloaded') were prescribed to provide a sufficient span of stimuli to promote peak power production. Following an unloaded sprint, loading was increased in factors of 20% of BM (up to 120% BM) until a ~ 50% decrement in unloaded maximum velocity (i.e. v_{max}) and a visual peak of power output was observed. Sprints were performed on a marked indoor Mondo athletics track, under the following pre-set distances: 45 m unloaded; 40 m at 20% BM; 30 m at 40% BM; 30 m at 60% BM; 30 m at 80% BM; 20 m at 100% BM; and 20 m at 120% BM (amended intra-assessment to avoid the accumulation of unnecessary fatigue).

Data analysis

Two main methods of analysis were used for this study: (1) The assessment of force–velocity relationships from the acceleration phase of the initial unloaded sprint (single trial method); and (2) computation using kinetic data from each of the resisted trials (developed at maximal resisted velocity) compiled into a single composite relationship (i.e. multiple trial method). In both cases the raw velocity–time data of all trials were fit with a mono-exponential function (Cross et al. 2017b). Both analysis processes were completed using separate pathways of a custom LabVIEW platform (Build version: 14.0, National Instruments Corp., Austin, TX, USA).

Single trial method

External force production was modelled from centre of mass movement via the application of a validated method, described in significant detail elsewhere (Samozino et al. 2016). Briefly, using a macroscopic approach the acceleration and horizontal orientation of the athlete's centre-of-mass can be conveyed

after v over time, enabling the net horizontal antero-posterior ground reaction forces (F) to be modelled when considering the mass (m; system mass) of the athlete performing the sprint, and resistance due to aerodynamic friction force (F_{aero}) (Cross et al. 2017b):

$$F = m \cdot a + F_{aero} \qquad (1)$$

F_{aero} was computed throughout the sprint from horizontal velocity and estimated drag coefficients (Arsac and Locatelli 2002; van Ingen Schenau et al. 1991). Mean net horizontal antero-posterior power output (P) is then modelled at each instant as the product of F and v:

$$P = F \cdot v \qquad (2)$$

Multiple trial method

The multiple trial method derives from the same fundamental principles of dynamics, however in this case because variables were quantified at peak velocity during each trail (i.e. v_{max}), it was assumed zero acceleration was occurring. Therefore, at the instance of v_{max} the variable F (F_{peak}) is equal to the sum of F_{aero} and kinetic friction force (F_f) from the resisted sled (Cross et al. 2017c):

$$F_{peak} = F_{aero} + F_f \qquad (3)$$

F_{aero} was determined via the same methods used in the single trial method. The computation of F_f is calculated as a portion of normal load (F_n; the total sled mass under gravity [-9.81 m s^{-2}]), dependent on the coefficient of kinetic friction (μ_k) between the sled and track surface. These methodological proceedings are detailed in depth in a previous publication (Cross et al. 2017c). Briefly, a 'sliding-friction' approach was used to experimentally determine the external force expressed during a sled sprint. Identical surface, equipment and equated environmental conditions were used to those featured in the current experiment. A winch (Model: CMP100M Servo gear motor, SEW-Eurodrive, Auckland, NZL) pulled our sprinting sled across the surface of the testing track under two different conditions: constant speeds with variable sled mass, and constant sled mass with variable speed. For each trial, towing velocity was measured directly from the winch, and force–time data were collected using a wireless load-cell connected in-line with the sled and attached cable. In this manner, friction force could be measured and compared under a given towing velocity and sled-load parameter. While the conversion between normal and friction force is typically considered to be independent of velocity, the coefficient of friction was found to be independent of normal force, and instead change with velocity; resulting in a parabolic fit. As such, for a given sled loading parameter F_f can be estimated using the following equation(s):

$$F_f = (\mu_k \cdot F_n)/(\cos\theta + \mu_k \sin\theta) \qquad (4)$$

with μ_k as equal to the polynomial fit, dependent on the towing velocity (in this case v_{max}):

$$\mu_k = -0.0052v_{max}^2 + 0.0559v_{max} + 0.3184 \qquad (5)$$

Final kinetic data were corrected to account for angle of pull between the attachment of the tether to the athlete and sled (θ):

$$\theta = \sin^{-1}\left((h_t)/c\right) \qquad (6)$$

where, h_t is the height of attachment to the athlete in standing posture standing, and c is the tether length in radians. P at v_{max} for each trial was modelled as per Eq. (2), with F and v substituted with F_{peak} and v_{max}. The outcome variables assessed using this method have been shown to be reliable in recreational level athletes (Cross et al. 2017a).

Force–velocity and power–velocity relationships and optimal loading conditions

Fv and Pv relationships were generated for individual athlete using both single and multiple trial methods. For both methods, F and v were plotted against each other under least-squares linear regressions (individual athletes: $R^2 > 0.99$ for the multiple-trial method, and > 0.99 for the single trial method; $P < 0.0001$), and P and v were plotted using 2nd order polynomial fits ($R^2 > 0.98$ for the multiple-trial method, and > 0.99 for the single trial method; $P < 0.0001$). In the case of the single trial method, this comprised of instantaneous values throughout acceleration (Samozino et al. 2016), for the multiple sprint method single values of each variable were obtained from each sprint to compile a single relationship representing athlete ability under increasing loading (Lakomy 1987). F_0, v_0 and S_{Fv} were determined as the graphical intercepts of the Fv relationships and the regression slope (respectively). P_{max} was determined as the apex of the quadratic Pv relationships using the first mathematical derivation of the associated quadratic equation. Optimal conditions for power (v_{opt} and F_{opt}) were calculated at the point of P_{max}, corresponding to $0.5 \cdot v_0$ and $0.5 \cdot F_0$. L_{opt} was calculated in the same manner for both trials, using an inverse computation to determine the normal loading of the sled corresponding to the peak of the Pv relationship (i.e. v_{opt} and F_{opt}). Practically, the final L_{opt} would present horizontal resistance equal to F_{opt} (when combined with F_{aero}), and a maximum resisted velocity equal to v_{opt}; the result being a sprint where maximum velocity is attained in the precise conditions of P_{max}, graphically represented as the peak of the Pv curve (see Fig. 1).

Fig. 1 Graphical representation of an Fv relationship compiled using a multiple sprint relationship. The data presented are from a rugby player (stature 1.80 m; body-mass 89.56 kg)
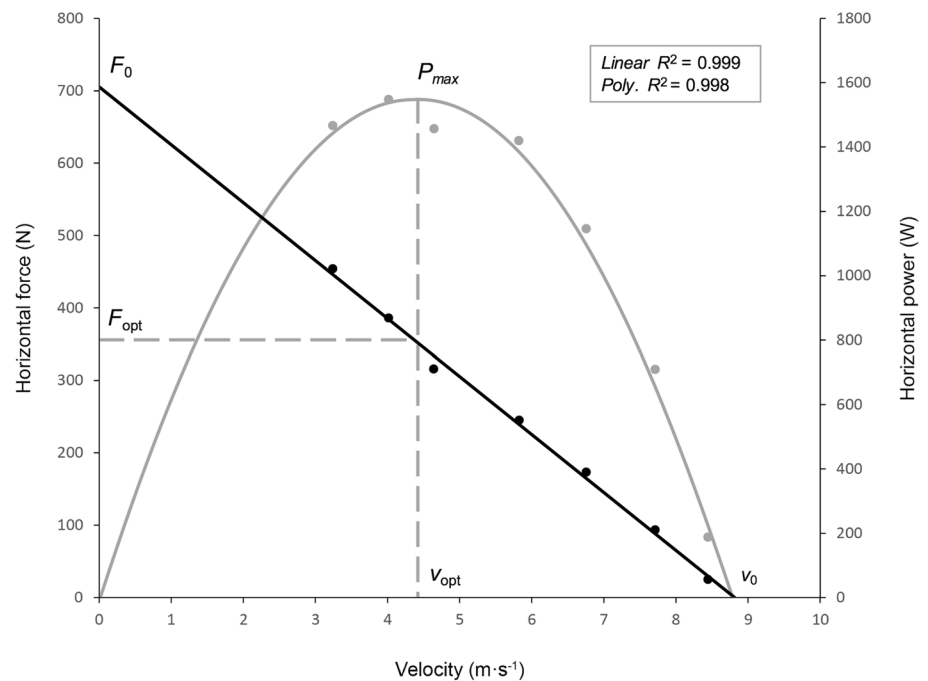
Statistical analysis

Descriptive statistics are presented as means ± standard deviation. Comparisons between the multiple sprint and single sprint method used linear regressions and absolute bias ± 90% confidence intervals. Strength of agreement was assessed using Pearson's correlation coefficient (r), with threshold values of 0.3, 0.5, 0.7, 0.9, and 1.0, representing weak, moderate, strong, very strong and perfect relationships, respectively. Magnitude of error was expressed as the typical error of estimate (TEE) in raw and standardised units [effect size (ES)], using a modified Cohen's scale to provide qualitative inferences: 0.1, 0.3, 0.6, and > 0.6 to represent trivial, small, moderate, and large, respectively (Hopkins et al. 2009). The calculated error was doubled to better interpret its true magnitude. Statistics were calculated using a modified statistical Excel spreadsheet from sportsci.org (*xvalid.xls*), using the single trial method as the criterion.

Results

See Table 1 for full description of results from analyses. The average relative bias between the methods was between − 6.4 and − 0.4% (towards the single sprint method). Velocity based measures were the most well matched (very strong correlations), with little bias (− 1.4 and − 0.4%) and small levels of error. While still exhibiting strong correlations, measures of force and power exhibited large levels of error between approaches. Figure 2 presents a graphical

representation of the comparison of the Fv profiles obtained from the two methods.

Discussion

Overall, Fv relationships determined from multiple resisted trials and a single free sprint were well comparable, corroborated by an overall low bias and strong to very strong (almost perfect) correlations for key mechanical variables. Despite these encouraging factors, inflated absolute error was associated with increasing loading and associated external force, which may serve to highlight movement discrepancies or methodological shortcomings in modelling Fv relationships using multiple trial resisted sprint methods. The cause and practical impact of this error requires further investigation.

Overall, the capacity to produce horizontal power was strongly related between methods ($r = 0.84$), albeit a trend for lesser magnitudes in the multiple trial method (− 5.7% bias), and with larger error scores (ES = 0.55 to 0.57). The ability to generate force at high velocities (v_0) was almost perfectly related between methods ($r = 0.99$), with small levels of error (ES = 0.13). This result was somewhat expected, given the unloaded sprint featured as a data-point in the composite multiple trial method (with F simply equal to F_{aero}). Force at low velocities presented a lesser (albeit strong) correlation ($r = 0.71$) with increased levels of error (large; ES = 0.71). A mean bias of lower output from the multiple-trial method may be reminiscent of the increased muscular effort required to overcome similarly increased inertia under greater loading protocols incrementally impeding v_{max} ability. This increased

Table 1 Comparison of mechanical relationships and optimal loading variables between single and multiple sprint methods

Mechanical variables	Single sprint (Mean ± SD)	Multiple sprint (Mean ± SD)	Single vs. multiple sprint methods		
			Absolute bias (90% CI)	Pearson's (r)	Typical error estimate (absolute; inference)
Force–velocity–power relationship					
v_0 (m·s^{-1})	9.27 ± 0.86	9.13 ± 0.80	− 0.14 (− 0.18; − 0.09)	0.99	0.11; Small
F_0 (N)	589 ± 81	562 ± 76	− 26.65 (− 46.65; − 6.64)	0.71	58.8; Large
S_{Fv}	− 63.8 ± 8.41	− 61.8 ± 9.34	− 1.96 (− 4.16; 0.23)	0.73	5.94; Large
P_{max} (W)	1370 ± 260	1286 ± 219	− 84.75 (− 132.37; − 37.14)	0.84	147.9; Large
Optimal loading characteristics					
F_{opt} (N)	294 ± 40	281 ± 38	− 13.51 (− 23.45; − 3.58)	0.72	29.17; Large
v_{opt} (m s^{-1})	4.60 ± 0.43	4.58 ± 0.40	− 0.02 (− 0.04; 0.00)	0.99	0.053; Small
L_{opt} (kg)	67 ± 9.2	64 ± 8.9	− 3.10 (− 5.42; − 0.78)	0.71	6.71; Large

v_0 theoretical maximum velocity, F_0 theoretical maximum force, S_{Fv} slope of the linear force–velocity relationship, P_{max} peak power, F_{opt} force at peak power production, v_{opt} velocity at peak power production, L_{opt} normal loading at peak power production, m s^{-1} metres per second, N Newtons, W watts, kg kilogrammes

Fig. 2 Comparison between multiple and single trial force–velocity–power methods. Solid black line represents the mean Fv relationship determined from the multiple sprint method. The white line, and grey surrounding area represents the 90% confidence limits of the predictive equation between the two relationships
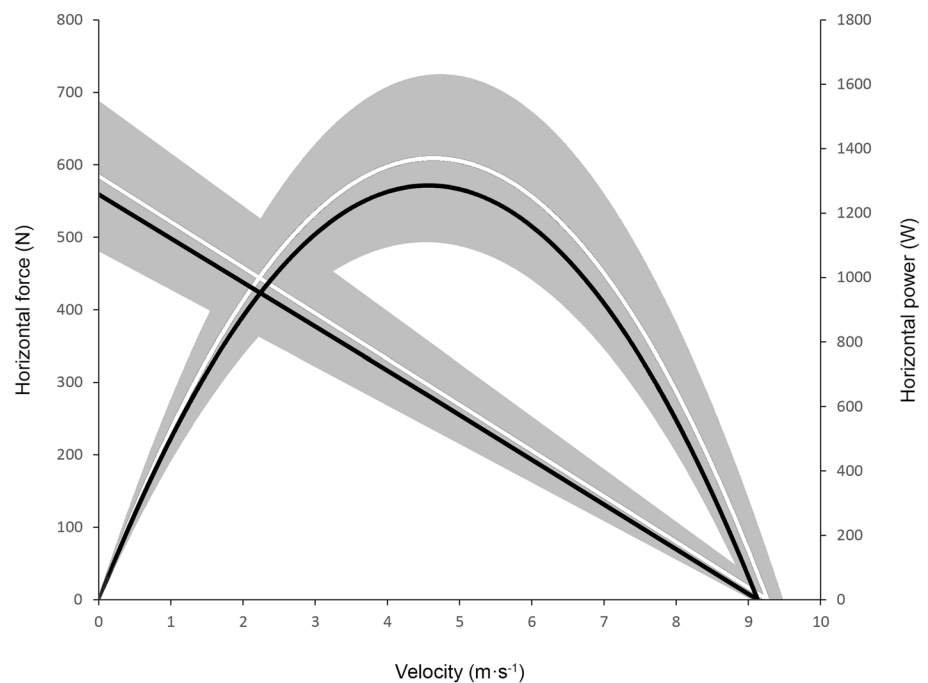
muscular effort is not accounted for in the multiple sprint model, and consequently may have resulted in progressively larger disparities between methods closer to the *y*-axis. This intra-trial fatigue has been discussed at length in the sprint cycling literature (Driss and Vandewalle 2013), where P_{max}

has typically been shown to be ~ 10% greater when using a single-trial 'corrected' approach (Cross et al. 2017b).

There were large errors associated with increased horizontal force output (i.e. heavier loading; F_0) between the two methods. The cause for this error is difficult to ascertain,

as at face value the individual Fv and Pv relationships for all athletes were very accurately plotted across both methods. Moreover, both multiple (Cross et al. 2017a) and single trial (Samozino et al. 2016) approaches have been shown to provide acceptable inter-test reliability scores for force and velocity data. Perhaps the simplest explanation is that some degree of error is unavoidable when adding resistance of substantial magnitudes to such a complex movement as sprinting. The extent of familiarity may have plausibly contributed to athletes responding 'positively' or 'negatively' when loading was progressively applied to the system, based on their experience with resisted sprinting technique (e.g. ~ 2 sessions to ~ 10 years). Another possibility is that comparing the two assessment modalities inflated the error score as a product of the interaction between the errors associated with each test in unison (coefficient of variation scores of 1.1–2.9 and 1.1–4.6% for single trial and multiple trial, respectively). While not entirely feasible for the multiple trial method, using an average of several test scores should provide a clearer indication into the true similarities and differences between the two approaches. To better assess and understand this interplay of factors, we encourage researchers to undertake further, more-detailed biomechanical analysis in this area.

In calculating the conditions for optimal loading, the multiple trial method presented a lesser L_{opt} by ~ 3.1 kg ($-4.5 \pm 3.4\%$). Given the adaptations of training at various resistive loads have yet to be clearly clarified, it is unclear whether this practically represents a worthwhile margin of error (~ 1.3 kg of resistance experienced by the athlete) (Cross et al. 2017c). With an almost perfect correlation, a raw mean difference of -0.02 m s^{-1}, and small error (ES = 0.12), there is high agreement between methods for the assessment of v_{opt} ($r = 0.99$). This strong relationship would be indicative of a possible avenue for the assessment and prescription of training load from a single sprint, without the need for multiple taxing resisted sprint trials. Proving somewhat of a circular problem, the limitation of such an approach is the translation of v_{opt} into a useable training resistance, which requires assessment of the magnitude of stimulus presenting said velocity decrement; a factor that can change drastically based on surface conditions and equipment (e.g. different sled) (Cross et al. 2017c). Nevertheless, a notable conceptual finding from this study is that L_{opt} could conceivably be determined from a single unloaded sprint, permitting the friction coefficients of the resistive device and environment are known. In particular, this method may prove valuable when using devices that are not subject to significant fluctuations in resistance due to changing friction and environmental conditions, such as wall-mounted pulley systems or winch based isokinetic devices. Another option is to use a multiple trial method with a reduced number of loading protocols (e.g. 2–4, including an unloaded

sprint) (Jaric 2016), although it is likely athletes will need to be thoroughly accustomed to the testing modality before accurate and reliable results can be attained from smaller trial numbers. Nevertheless, future research is necessary to qualify the training effects of individualised horizontal training application, including adaptation sensitivity to the magnitude of changes in loading that may result from roaming friction or other factors. While we hypothesise the latter, it is possible that in many cases changes in resistance due to friction simply do not constitute a large enough effect in training outcomes to warrant the attention of general practitioners.

The most important and practical finding from this experiment is the overall strong association between the composite relationships determined via free sprinting and multiple resisted sprinting trials ($r = 0.71$ to 0.99). That is, while error exists, the relationships developed from each method are characteristically similar. Although this finding is expected when read in unison to the extensive literature on multiple vs. single trial methods in cycling (Driss and Vandewalle 2013), to our knowledge the interplay between the two methods has not been tested or discussed in sprinting. Practically, maintaining a maximal sprint effort at a given resistive load may replicate the conditions experienced during an unresisted sprint trial, associated to the relative section of the Fv relationship (see Fig. 3 for a graphical representation). In the example of an athlete towing individualised L_{opt} (e.g. ~82%BM), sprinting in these conditions mimics the moment power is maximised during an unloaded sprint [i.e. steps 2–3, or early acceleration (Rabita et al. 2015)]. These results provide evidence that a section of the sprinting acceleration phase can potentially be targeted and improved based on prescription of individualised loads from the Fv relationship (Jimenez-Reyes et al. 2016); albeit with assumption of some inaccuracy due to error and potentially reduced 'direct' transfer when using loading protocols of greater magnitude. As a result, training performed under a given resisted sprinting loading condition may transfer to phase-specific adaptations in unloaded free sprinting. It is important to note that while this theory highlights that very heavy loads previously rebuked (Alcaraz et al. 2009) may show promise in the development of maximum horizontal force or power at low velocities (i.e. beginning of a sprint acceleration) (Cross et al. 2017b; Morin et al. 2017), lighter loads traditionally used in research (or even 'assisted' methods) likely have relevance in the development of horizontal force at high velocities—a capacity central 'pure-speed' and 'velocity specific' athletes (Morin et al. 2012). Consequently, all loads may indeed express contextual specificity in external Fv characteristics, and blanket avoidance of these training loads may be misplaced (depending on training goals).

While this study provides evidence to support the transfer between resisted sprinting and unloaded sprinting Fv profiles, caution should be exercised when interpreting these

Fig. 3 A graphical representation of the theory presented in this study. The force velocity data corresponding to a single sprint (represented in the sprinter below the *x*-axis) can be overlaid with a spectrum of horizontal resistance (represented in the weighted sled, to the left of the primary *y*-axis). To summarise the theory, it is possible to select a load and approximate a phase-specific effect, based on phase-specific mechanical demands. Note that loading is context-specific and can be heavily reliant on environmental conditions (e.g. friction)
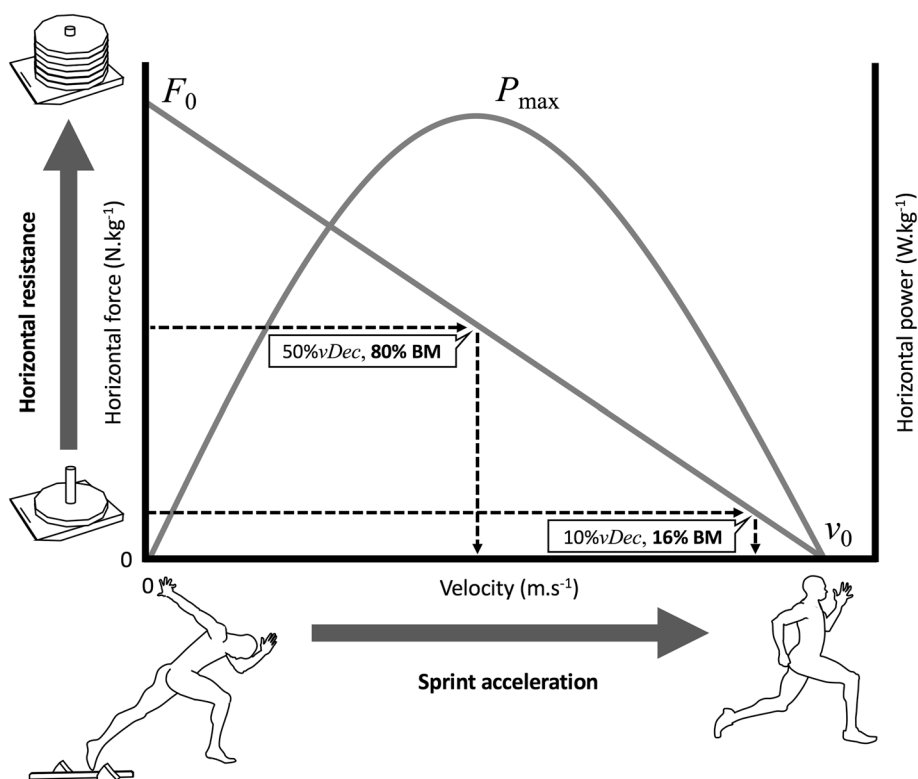
results. Although there are some preliminary training data that suggest training in conditions of high-force and power may show promise for the targeted development of specific Fv capacities (Morin et al. 2017), given the complexity of sprinting performance many other factors will contribute to the adaptations observed (e.g. pre-training capabilities). In any case, a training program developed based on this loading model should factor as part of a periodised holistic programme including varying degrees of technical, unloaded, resisted and assisted sprint work, and general conditioning practices - individualised, and altered depending on athlete sporting code or level. Future studies should look to build on these theories using interventions with a span of loading protocols to assess the longitudinal effects of targeted training on Fv relationships, practical performance measures and technical markers.

Limitations

The testing was performed using a non-randomised, incremental process of loading necessitated by the experimental design of multiple trial methods (Vandewalle et al. 1987). Consequently, while this was necessary for the purposes of determining when to cease the assessment and despite sufficient resting periods between loaded sprints, fatigue or other interactions may have caused some disparities between the two relationships as a product of the unloaded

sprint being performed first, and multiple trial method being second (i.e. comprising of the subsequently performed loaded sprints).

Conclusions and practical applications

- Approximated optimal loading can be determined from a single sprint, providing friction coefficient characteristics of the testing and training surface are known. Importantly, optimal velocity determined from a single sprint may have valuable application to other resisted sprint modalities (e.g. isokinetic sprint drums).
- Light resistance (e.g. ~ 10% decrement in v_{max}) likely provides an effective stimulus for development of horizontal force at high velocities. However, training using greater loading protocols (e.g. > 50% decrement in v_{max}) may provide a more effective overload for the development for short distance sprint performance (i.e. force and maximum power).
- The cause for the increased error between the methods warrants further investigation. For example, whether it constitutes a worthwhile magnitude with regards to training adaptations. Until which time, readers are cautioned to interpret the mechanical conditions experienced during sled sprinting to be mechanically similar, but not identical.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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