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Optimal Loading for Maximizing Power During Sled-Resisted Sprinting

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***Purpose**:* To ascertain whether force-velocity-power relationships could be compiled from a battery of sled-resisted overground sprints and to clarify and compare the optimal loading conditions for maximizing power production for different athlete cohorts. ***Methods**:* Recreational mixed-sport athletes (n = 12) and sprinters (n = 15) performed multiple trials of maximal sprints unloaded and towing a selection of sled masses (20–120% body mass [BM]). Velocity data were collected by sports radar, and kinetics at peak velocity were quantified using friction coefficients and aerodynamic drag. Individual force–velocity and power–velocity relationships were generated using linear and quadratic relationships, respectively. Mechanical and optimal loading variables were subsequently calculated and test–retest reliability assessed. ***Results**:* Individual force–velocity and power–velocity relationships were accurately fitted with regression models ($R^2 > .977$, $P < .001$) and were reliable (ES = 0.05–0.50, ICC = .73–.97, CV = 1.0–5.4%). The normal loading that maximized peak power was 78% ± 6% and 82% ± 8% of BM, representing a resistance of 3.37 and 3.62 N/kg at 4.19 ± 0.19 and 4.90 ± 0.18 m/s (recreational athletes and sprinters, respectively). Optimal force and normal load did not clearly differentiate between cohorts, although sprinters developed greater maximal power (17.2–26.5%, ES = 0.97–2.13, $P < .02$) at much greater velocities (16.9%, ES = 3.73, $P < .001$). ***Conclusions**:* Mechanical relationships can be accurately profiled using common sled-training equipment. Notably, the optimal loading conditions determined in this study (69–96% of BM, dependent on friction conditions) represent much greater resistance than current guidelines (~7–20% of BM). This method has potential value in quantifying individualized training parameters for optimized development of horizontal power.

***Keywords**:* mechanical profiling, sprint training, horizontal force

The maximal power-production ability of the human body has been studied extensively, and its relationship to general athletic performance is well accepted in both research and applied communities.[1,2] The assessment of power and its mechanical determinants provides insight into the limits of the neuromuscular system for explosive performance and is valuable in sports featuring regular maximal-exertion activities such as sprint acceleration.[3,4]

Traditionally, researchers have assessed the ability of the lower extremities to produce power using multisegmental exercises (eg, cycling, jumping, horizontal limb extension, and sprinting), with athletes performing multiple trials against a selection of progressively increasing resistance conditions.[5] This results in data corresponding to decreasing velocity (typically described in maximum velocity attained each trial), with increasing resistive force (or load) and associated increased force production—a linear force–velocity (Fv) relationship.[6] The theoretical x- and y-axis intercepts of this relationship (theoretical maximum force the system can produce at zero velocity [F_0]; the theoretical maximum velocity the system can generate at zero force [v_0]) characterize the maximum capacity of an individual.[7] Power can be computed at any point as the product of force and velocity ($P = F \times v$), with the relationship between power and velocity (Pv) fitted with quadratic equations.[7] The peak of the Pv relationship represents maximum power (P_{max}), otherwise determined via the equation $(F_0 \times v_0)/4$.[6] P_{max} ability is generally considered a criterion of performance and is widely measured and presented in variants of athlete groups and abilities.[2]

An aim of profiling power over multiple trials is determining the metrics that combine to present P_{max}.[8] Often termed optimal,[1,2] these conditions are represented in optimal force (F_{opt}) and optimal velocity (v_{opt}) (Figure 1[A]) and the associated external loading protocol (L_{opt}) responsible for generating the conditions necessary to maximize power. While determining optimal loading is useful for comparative analysis, performance monitoring, and application in competition scenarios in limited examples,[9] its greatest value lies in training implementation.[10] In particular, the assessment of power using multiple resisted trials allows the operator to quantify an exact resistance protocol that can be easily integrated into training (if assessed in a specific and practical environment).[2,8,10] Training around optimal conditions for power is generally viewed as an effective means of improving P_{max},[8] with evidence of benefits in a variety of neuromuscular and physiological capacities.[11] These factors strengthen the rationale for profiling optimal loading characteristics where their inclusion in training is relatively straightforward.

Until recently, authors examining force-velocity-power (FvP) relationships in sprinting have used specialized sprint treadmill ergometers.[12] Based on operational methods from cycling, athletes perform multiple sprints against increasing braking resistance to the belt (electromagnetic or motor braking),[12,13] after which individualized optimal loading conditions may be determined.[14] Three studies have examined optimal loading characteristics across multiple treadmill sprints,[14–16] although none calculated the exact conditions for P_{max} with respect to plotting FvP relationships. In any case, dissimilarities between treadmill and overground sprinting[17] and

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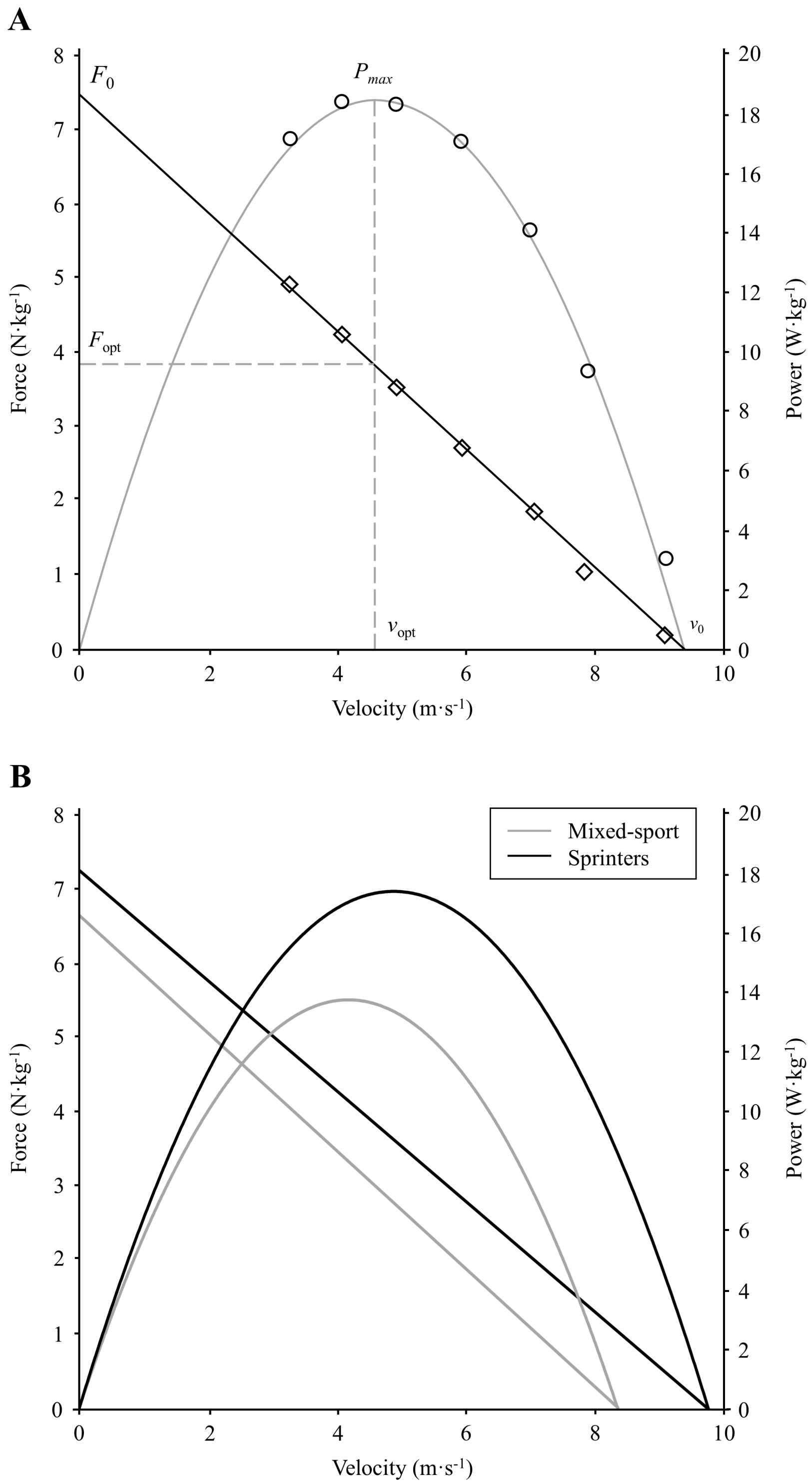

Figure 1 — (A) Graphical representation of the force–velocity and power–velocity relationship profiled via a multiple-trial method using resisted sleds. Data points represent values derived from single individual trials at different loading protocols. F_0 and v_0 represent the *y*- and *x*-intercepts of the linear regression and the theoretical maximum of force and velocity able to be produced in absence of their opposing unit. P_{max} represents the maximum power produced, determined as the peak of the polynomial fit between power and velocity. Furthermore, the graphical calculation of optimal force (F_{opt}) and velocity (v_{opt}) variables is shown. (B) Mean of individual force-velocity-power profiles of recreational athletes (gray lines) compared with sprinters (black lines).

limited access to such technology for training purposes render the results of this research of little use to general practitioners.

Power profiling during overground sprinting has been proven possible,[4,18] with authors highlighting the central role of horizontal power in performance. However, despite the prevalence of resisted-sprinting protocols in the literature (eg, sprinting sleds[10]), no attempt has been made to profile optimal loading conditions for maximizing power production. Therefore, the aims of this study were to assess whether a multiple-trial method, using resisted-sprint sleds to supply resistance, could be used to accurately and reliably profile *FvP* relationships during overground sprinting; quantify and present optimal loading conditions for maximizing power; and compare mechanical characteristics between highly trained sprinters and recreational cohorts.

Methods

Participants

Twelve recreational-level mixed-sport athletes and 15 highly trained sprinters gave their written informed consent to take part in this study after being made aware of the procedures, risks, and benefits of study participation. The 2 cohorts were selected to provide a proof of concept for the applicability of the profiling method to both athletes highly familiar with resisted sprinting and athletes with mixed familiarity levels. Sprinters were required to have attained a performance standard of at least 750 IAAF (International Association of Athletics Federations) points[19] in an event ≤400 m within the previous season. The mean (± SD) current (within-season) performance level of the group was 883 ± 126 IAAF points[19] in their primary event, including 3 national champions and record holders. At least 2 years of sprint-training experience was required, including ≥1 year using resisted-sprint methods. Athletes were devoid of lower-extremity injuries (>3 mo pretesting) and were either determined as familiar with the testing modality (ie, having performed resisted sprinting with loads ≥50% of body-mass [BM]) or were provided with a familiarization session >72 hours pretesting (n = 3). The study was approved by the Auckland University of Technology ethics committee (#15/61).

Design

This study sought to investigate whether multiple trials of sled-resisted sprints could be used to determine mechanical relationships, and optimal loading for maximizing horizontal power, in recreational and sprint cohorts. A repeated-measures protocol was implemented to measure the changes in performance, determined from a combination of aerodynamic drag, friction force, and maximum velocity across sprint trials while resisted by a range of sled loads. Recruitment and subsequent testing occurred throughout the competitive track and field season of 2015. Intersession test–retest reliability of all variables was assessed in 9 recreational athletes, who performed 2 testing procedures separated by 7 days. Reassessment took place using identical testing parameters to the first session, at the same time of day to minimize diurnal fluctuations, with athletes asked to standardize their surrounding activities. All testing occurred after ~24 hours rest.

Methodology

All testing procedures were completed in the same running lane of an indoor Mondo track. Athletes were instructed to wear their typical footwear for maximal sprinting. Recreational athletes wore standard athletic footwear, and sprinters wore sprinting spikes. A standardized ~30-minute warm-up including jogging, dynamic stretching, and submaximal 45-m stride-outs (70%, 80%, and 90% of maximal self-selected effort) was performed. A 5-minute active-recovery period directly preceded the commencement of testing, during which procedures were verbally recommunicated. The testing battery consisted of 6 or 7 sprints up to maximal velocity (v_{hmax}), performed with increasing sled loading, interceded by 5 minutes passive rest.

For each trial, the athlete would step up to a marked line on the track and sprint forward from a standing split stance without countermovement. In trials requiring the athletes to be resisted by a sled, they were instructed to take up all slack in the tether before propelling themselves forward, to ensure that there was no "jerking" or "bouncing" of the sled. For each sprint trial, athletes were verbally encouraged to ensure a full maximal-effort sprint devoid of any purposeful deceleration. Athlete performance was measured throughout each sprint by means of a sports radar device (Model: Stalker ATS II, Applied Concepts, Dallas, TX, USA), set on a heavy-duty tripod 5 m behind the athlete at a height approximating center of mass (~1 m). The device has been shown to be valid and reliable[20] and was operated remotely via laptop to collect forward velocity–time data at a rate of 46.9 Hz via the manufacturer-supplied software package.

For resisted trials, a heavy-duty sprint sled (5.64 kg; Get-Strength, Model: HT 50 mm Sled, Auckland, New Zealand) was attached to a specialized harness (0.34 kg; XLR8, Model: SA1 PM, Wellington, New Zealand; attachment point midlow back) worn by the athlete, via a 3.3-m nonelastic nylon tether and high-tensile karabiners. The sled was engineered from folded stainless steel with smooth flat railings contacting the track surface. Calibrated plates (Model: PL Comp Discs, Eleiko Sport, Halmstad, Sweden) supplied normal loading for the testing protocols. Seven loading protocols (unloaded and 20%, 40%, 60%, 80%, 100%, and 120% BM) were prescribed to provide a sufficient span of stimuli to capture the peak and ascending limb of the power–velocity (*Pv*) curve (determined from pilot data). Loading was increased until a >50% decrement in unloaded v_{hmax} and a visual peak of the parabolic *Pv* relationship were observed, which was monitored throughout testing using a customized Excel spreadsheet and raw unfiltered radar data from each sprint. Distances for each load were selected from pilot data as an exaggeration of what was required to reach v_{hmax}, as follows: 45 m unloaded, 40 m at 20%, 30 m at 40%, 30 m at 60%, 30 m at 80%, 20 m at 100%, and 20 m at 120% BM (marked with parallel cones). Distance of v_{hmax} was monitored throughout testing, and where necessary subsequent trial distances were modified to ensure that athletes were not sprinting for unnecessary lengths of time or missing their potential v_{hmax}.

Data Analysis

All velocity–time data collected via the STATS software were initially clipped at the point of deceleration (Figure 2) and analyzed using a custom-made LabVIEW program (Build version: 14.0, National Instruments Corp, Austin, TX, USA).

Application of Exponential Function

The velocity–time signal of maximal sprinting is well described by a monoexponential function.[18,21] In this method, instantaneous velocity–time data are plotted via the equation[22]

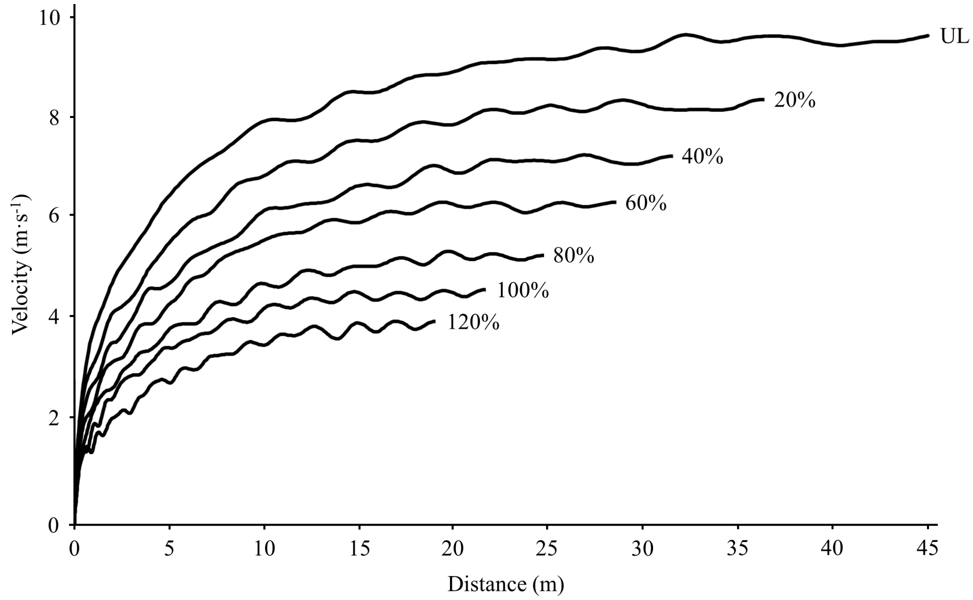

Figure 2 — Graphical representation of the clipped raw velocity–distance radar data. Seven sled trials are pictured, clipped before deceleration occurred. From the trial with the highest v_{hmax} (UL, unloaded sprint), the loading ranges from 20% to 120% of body mass with each trial.

$$v_h(t) = v_{hmax} \times (1 - e^{-t/\tau})$$

where v_{hmax} represents the maximal velocity reached during overground locomotion in meters per second and τ the acceleration time constant in seconds. The mean fit of the equation was R^2 = .999. From here, kinetic variables were calculated at the instant of v_{hmax} (ie, maximum sled-resisted velocity) for each trial. The main reasoning behind the selection of calculation at v_{hmax} was based on the simplicity of calculation and subsequent replication for future practitioners and to provide a training condition that could be artificially extended during practice (ie, maintenance of maximal resisted velocity) to allow athletes to work in their conditions for maximum power for a lengthened period of time (rather than a single instant experienced during acceleration).

Mechanical Data

The fundamental principles of dynamics in the horizontal direction enable the net horizontal anteroposterior ground-reaction forces to be modeled for center of mass. In the case that assessing these variables at v_{hmax} acceleration is assumed to be null, the equation represents $F_{hpeak} = F_{aero} + F_f$, with horizontal force at v_{hmax} (F_{hpeak}) equal to the aerodynamic friction of the body in motion (F_{aero}) and kinetic friction force from the resisted sled (F_f). The model used for the estimation of F_{aero} has been described in detail elsewhere.[18] Consequently, to enable calculation of air density for F_{aero}, temperature (16.5°C ± 1.69°C) and barometric pressure (756 ± 5 Torr) were recorded from each session using a portable weather unit.

Model for Kinetic Friction Force

To determine the conversion of sled weight to friction force, a sliding-sled experiment was performed (unpublished data). A mechanical winch (Model: CMP100M Servo gear motor, SEW-Eurodrive, Auckland, New Zealand) was used to pull the testing sled, with a constant load (55.6 kg) and varying velocities (0.1–6 m/s), on the testing track. Normal force (F_n) was compared against F_f at each velocity, resulting in a parabolic fit. F_f can be estimated, including correction for angle of pulling (θ), using the following equation:

$$F_f = (\mu_k \times F_n)/(\cos\theta + \mu_k \sin\theta)$$

where μ_k is equal to coefficient of kinetic friction and F_n is the total weight of the sled (in Newtons, the total sled mass under gravity [–9.81 m/s²]). μ_k and θ are estimated using the equations

$$\mu_k = -0.0052 v_{hmax}^2 + 0.0559 v_{hmax} + 0.3184$$

where μ_k is equal to a quadratic equation including instantaneous velocity (in this case v_{hmax}), and

$$\theta = \sin^{-1}(h_t/c)$$

where h_t is the attachment height of the tether to the athlete while standing and c is the length of the tether in radians.

FvP Relationships and Optimal Loading

Power at v_{hmax} (P_{hpeak}) is calculated as $v_{hmax} \times F_{hpeak}$. Fv and Pv relationships were generated for each athlete as a composite of data from each loading condition.[13] F_{hpeak} and P_{hpeak} were plotted against v_{hmax} for each trial, and the compiled data were fitted with least-square linear and second-order polynomial regressions, respectively.[18] The unloaded trial was included as a data point, with the resistance in this case being equal to F_{aero}. F_0 and v_0 were determined as the force and velocity axis intercepts resultant of extrapolating the composite Fv relationship, with S_{Fv} as the slope. P_{max} was determined as the apex of the quadratic Pv relationship for each individual, and as P_{max} 2 = ($F_0 \times v_0$)/4.[6] Bias between P_{max} and P_{max} 2 was calculated as the difference between the 2 variables, expressed as a percentage of the reference value: (P_{max} – P_{max} 2)/P_{max}. v_{opt} and F_{opt} were identified as the levels of each respective variable at which P_{max} occurred. Optimal normal loading (L_{opt}; the total mass of the sled) was calculated via backward conversion from F_{opt} via the methods described herein. Relative variables were determined by dividing the given absolute value by total system mass (eg, BM with sled).

Statistical Analysis

Descriptive statistics are presented as mean ± SD of individual *FvP* relationships. Comparisons between athlete groups were completed using effect sizes (ES), 90% confidence intervals (lower limit; upper limit), and independent-samples *t*-tests ($\alpha = .05$). Magnitude-based inferences were calculated using a modified statistical Excel spreadsheet from sportsci.org (xParallelGroupsTrial.xls), and traditional statistics were calculated using a statistical software package (IBM SPSS Statistics 21, SPSS Inc, Chicago, IL, USA). The thresholds used in this study were based on the operational methodology of Hopkins et al (sportsci.org).[23] Probabilities that differences were higher, lower, or similar to the smallest worthwhile difference (ES = 0.2) were evaluated qualitatively as possibly, 25% to 74.9%; likely, 75% to 94.9%, very likely, 95% to 99.5%; and most (extremely) likely, >99.5%. The true difference was assessed as unclear if the chance of both higher and lower values was >5%. Intertest reliability of each variable was quantified by the coefficient of variation (CV in %), intraclass correlation (ICC), and the standardized change in the mean (ES; using threshold values described earlier) between the 2 testing occasions.[24]

Results

Tables 1, 2, and 3 display the descriptive and between-groups comparative statistics for athlete characteristics and *Fv* and *Pv* relationships, respectively. Values of F_0, L_0, v_0, P_{max}, P_{max} 2, S_{Fv}, F_{opt}, L_{opt}, and v_{opt} are presented with respect to the relationship from which they were determined. Where applicable, values were also expressed as relative to BM. Table 4 presents test–retest reliability. For all cases in both athlete groups, *Fv* relationships were well fitted by linear regressions, and *Pv* relationships were well fitted by second-order polynomial regressions (individual R^2 scores .994–.999 and .977–.997 for sprinters and .995–.999 and .979–.996 for mixed-sport athletes, for linear and polynomial regressions respectively; $P < 0.001$). A graphical example of mechanical characteristics is displayed in Figure 1(B), expressed as the mean of individual relationships for sprinters and recreational athletes (rather than regression fits to pooled data).

Discussion

To our knowledge, this study is the first of its type to investigate the ability to profile *FvP* relationships using a multiple-trial approach

Table 1 Descriptive Characteristics of Athlete Cohorts

Characteristic	Recreational athletes (n = 12), mean ± SD	Sprinters (n = 15), mean ± SD	Sprinters vs Recreational Athletes: Raw difference in means (±90% CI)	*P*	Rating
Age (y)	27 ± 4	24 ± 4	–5.4 (–8.2; –2.7)	.016	Large**
Stature (m)	1.76 ± 0.08	1.80 ± 0.04	0.038 (–0.0073; 0.082)	.18	Small**
Body mass (kg)	82.5 ± 10.47	78.1 ± 4.01	–4.4 (–10.1; 1.2)	.29	Small**
Maximum velocity (m/s)	8.12 ± 0.37	9.55 ± 0.29	1.4 (1.2; 1.7)	5E-11	Extremely large****
10-m-split time (s)	2.23 ± 0.086	2.02 ± 0.090	–0.21 (–0.27; –0.15)	2E-06	Very large****
30-m-split time (s)	4.85 ± 0.19	4.31 ± 0.13	–0.54 (–0.65; –0.43)	4E-09	Very large****

Note: For small, large, very large, and extremely large qualitative inferences: **likely, 75–94.9%; ***very likely, 95–99.5%; ****most (extremely) likely >99.5% effect when compared with recreational athletes. Recreational athletes comprised rugby union (n = 5), soccer (n = 3), American football (n = 2), lacrosse (n = 1), and weightlifting (n = 1) backgrounds. For sprinters, primary events comprised 100-m (n = 10), 200-m (n = 2), 400-m (n = 1), 110-m (n = 1), and 400-m hurdles (n = 1), with athletes typically meeting performance criteria across multiple disciplines (eg, 200- and 400-m).

Table 2 Summary of Force–Velocity Results for Recreational and Sprint Athletes

Mechanical variable	Recreational athletes, mean ± SD	Sprinters, mean ± SD	Sprinters vs Recreational Athletes: Raw difference in means (±90% CI)	*P*	Rating
Force–velocity relationship					
R^2	.997 ± .0013	.997 ± .0016			
$P^{(a)}$	1E-08	1E–08			
v_0 (m/s)	8.35 ± 0.38	9.75 ± 0.36	1.4 (1.2; 1.6)	7E-10	Very large****
F_0 (N)	558 ± 92	566 ± 63	8.3 (–45.9; 62.5)	.79	Trivial
rel F_0 (N/kg)	6.63 ± 0.53	7.25 ± 0.71	0.6 (0.2; 1.0)	.046	Moderate***
S_{Fv}	–66.6 ± 10.2	–57.9 ± 6.60	–8.7 (–14.6; –2.7)	.014	Moderate***
L_0 (kg)	188.5 ± 31.68	191.6 ± 21.3	3.1 (–15.4; 21.6)	.779	Trivial
rel L_0 (kg/kg)	2.28 ± 0.18	2.45 ± 0.24	0.18 (0.037; 0.31)	.105	Moderate**

Abbreviations: R^2, coefficient of determination; $^{(a)}$, mean significance value of individual regression fits for each cohort; v_0, theoretical maximum velocity; F_0, theoretical maximum force; rel, relative to body mass; S_{Fv}, slope of the linear force–velocity relationship; L_0, theoretical maximum normal load. Note: For trivial, small, moderate, very large, and extremely large qualitative inferences: **likely, 75–94.9%; ***very likely, 95–99.5%; ****most (extremely) likely, >99.5% effect when compared with recreational athletes.

Table 3 Summary of Power–Velocity and Optimal Loading Results for Recreational and Sprint Athletes

Mechanical variable	Recreational athletes, mean ± SD	Sprinters, mean ± SD	Sprinters vs Recreational Athletes: Raw difference in means (±90% CI)	P	Rating
Power–velocity relationship					
R^2	.989 ± .006	.987 ± .006			
$P^{(a)}$	2E-05	2E-05			
P_{max} (W)	1161 ± 223	1361 ± 171	200.1 (65.6; 334.6)	.017	Moderate***
rel P_{max} (W/kg)	13.77 ± 1.48	17.41 ± 1.81	3.6 (2.6; 4.7)	4E-05	Very large****
P_{max} 2 (W)	1168 ± 222	1381 ± 170	213.5 (79.4; 347.6)	.011	Moderate***
rel P_{max} 2 (W/kg)	13.85 ± 1.46	17.67 ± 1.80	3.8 (2.7; 4.9)	2E-05	Very large**
bias (%)$^{(b)}$	0.59 ± 0.71	1.50 ± 0.58			
Optimal loading conditions					
F_{opt} (N)	279 ± 46	283 ± 32	3.8 (–23.4; 31.0)	.81	Trivial
rel F_{opt} (N/kg)	3.37 ± 0.26	3.62 ± 0.36	0.25 (0.043; 0.45)	.12	Moderate**
v_{opt} (m/s)	4.19 ± 0.19	4.90 ± 0.18	0.71 (0.59; 0.83)	5E-10	Very large****
L_{opt} (kg)	64.4 ± 11.0	64.2 ± 7.3	–0.14 (–6.5; 6.3)	.783	Trivial
rel L_{opt} (kg/kg)	78 ± 6	82 ± 8	0.045 (–0.0031; 0.093)	.118	Small**

Abbreviations: R^2, coefficient of determination; $^{(a)}$, mean significance value of individual regression fits for each cohort; P_{max}, peak power production determined from the apex of the power–velocity relationship; rel, relative to body mass; P_{max} 2, peak power production determined from validated equation; $^{(b)}$ percent bias between P_{max} and P_{max} 2 for each cohort; F_{opt}, force at peak power production; v_{opt}, velocity at peak power production; L_{opt}, normal loading at peak power production. Note: For trivial, small, moderate, and very large qualitative inferences: **likely, 75–94.9%; ***very likely, 95–99.5%; ****most (extremely) likely >99.5% effect when compared with recreational athletes.

during overground sprinting. Overall, the results show that mechanical relationships generated from multiple sled sprints are accurately fitted with linear and quadratic equations, congruent with those observed in cycling,[6,25] treadmill sprinting,[26] and single-sprint overground methods.[18] We found that the loading spectrum of unloaded to 120% BM provided sufficient stimuli to clearly establish the peak of the Pv parabolic relationship for the testing conditions and athlete cohorts, shown both in the significant R^2 values and the visual fit of the data (ie, 2–3 data points around P_{max}). The bias observed between P_{max} and P_{max} 2 was minimal in both groups (0.6–1.5%), suggesting that P_{max} might be accurately determined using a lower number of sprints than in the current study. The method exhibits high test–retest reliability, strengthening its applicability for profiling and training in sports that involve sprint running and a need for horizontal power development.

Although resisted-sprint training is increasing in popularity, there is currently little mechanical evidence supporting the selection of loads for training implementation. By proving that the computation of FvP relationships using multiple trials of sled resistance was possible, this study was able to accurately determine individualized optimal loading parameters for maximizing power. Notably, all athletes presented optimal values of much greater magnitude than currently recommended[27,28] and used[10] in sprint-training literature, with F_{opt} shown to be 3.37 and 3.62 N/kg, equal to 78% and 82% BM (ie, L_{opt} for the present friction conditions) at 4.19 and 4.90 m/s (recreational athletes and sprinters, respectively). Optimal loading existed within a wide range for both cohorts (L_{opt} of 69–91% and 70–96% BM for recreational athletes and sprinters, respectively), highlighting the individualized nature of technical and mechanical Fv characteristics in both homogeneous and nonhomogeneous athlete groups.[7] Whether these ranges are due to disparate athlete characteristics (eg, mixed performance level and training backgrounds) or an accurate representation of the spread in physical capacities expected in a population requires more investigation.

The multiple-sprint method accurately profiled mixed-sport and well-trained sprinters alike (R^2 = .977–.999, P < .001), highlighting its value and applicability to a wide range of athletes. Comparisons between athlete subsets showed that sprinters exhibited greater P_{max} capacity than recreational athletes (18.3%, ES = 0.97), particularly when expressed relative to BM (26.4%, ES = 2.13). Similarly to previous findings[12] where velocity-dominant athletes towed the spectrum of lighter loads faster, the sprinters in this study displayed a much greater v_0 capacity than their recreational counterparts (16.8%, ES = 3.66). While differences in absolute force capacities were unclear, sprinters displayed moderately greater capacity when expressed relative to BM (9.4%, ES = 0.97). Relative F_{opt} and relative L_{opt} did not meet the alpha criterion for statistical significance (P > .05), likely resultant of the wide ranges in the values from both cohorts. When expressed as absolute values, differences were unclear. There was a very large effect, however, in the velocity at which the sprinters generated P_{max} (16.9%, ES = 3.73). These results appear to align with recent literature[3,4,26] highlighting that it is the ability to produce force at greater velocities that characterizes well-trained sprinters rather than absolute force-production ability. Given that Cross et al[21] have suggested that mechanical capacity for force at low velocities might be key to performance in acceleration-based collision sports, we would hypothesize that such athletes (eg, rugby forwards) would generate P_{max} at lower velocities than the averages seen in this study. This is only speculative, and future research should aim to determine optimal loading characteristics of force-dominant athletes and better profile contrasting athletic cohorts. Moreover, future studies should examine the impact of specialist footwear on sled-towing performance, as this may have contributed to the results observed.

Table 4 Reliability of Sled-Resisted Multiple-Trial Method (n = 9)

Mechanical variable	Change (ES)	CV%	ICC
Force–velocity relationship			
v_0 (m/s)	Small (0.5)	1.1	.92
F_0 (N)	Trivial (0.17)	4.6	.95
rel F_0 (N/kg)	Small (0.43)	4.5	.73
S_{Fv}	Trivial (0.18)	5.4	.91
L_0 (kg)	Trivial (0.13)	4.7	.97
rel L_0 (kg/kg)	Trivial (0.20)	3.4	.91
Power–velocity relationship			
P_{max} (W)	Trivial (0.15)	4.0	.97
rel P_{max} (W/kg)	Small (0.33)	4.0	.88
P_{max} 2 (W)	Trivial (0.15)	3.9	.98
rel P_{max} 2 (W/kg)	Small (0.34)	3.9	.88
F_{opt} (N)	Trivial (0.17)	4.6	.95
Rel F_{opt} (N/kg)	Small (0.30)	3.3	.78
v_{opt} (m/s)	Trivial (0.05)	1.0	.93
L_{opt} (kg)	Trivial (0.17)	4.8	.95
rel L_{opt} (kg/kg)	Small (0.47)	4.9	.68
Unloaded sprint			
v_{hmax} (m/s)	Trivial (0.0)	1.4	.90

Note: Values are change scores between sessions in standardized effect sizes (ES), coefficient of variation (CV%), and intraclass correlation coefficient (ICC). Abbreviations: v_0, theoretical maximum velocity; F_0, theoretical maximum force; rel, relative to body mass; S_{Fv}, slope of the linear force–velocity relationship; L_0, theoretical maximum normal load; P_{max}, peak power production determined from the apex of the power–velocity relationship; P_{max} 2, peak power production determined from validated equation; F_{opt}, force at peak power production; v_{opt}, velocity at peak power production; L_{opt}, normal loading at peak power production; v_{hmax}, maximum velocity.

Recent authors[3,4,26] have clearly shown that the determinants of sprinting ability are both the absolute physical capability of the body and the technical ability to apply this raw capacity in an effective manner. In the effort of preserving the latter skill, studies featuring resisted sprinting have often used or promoted comparatively light protocols, selected to minimize kinematic alterations to unloaded sprinting technique in both the maximal velocity and acceleration phases (7.5–15.5% decrements in velocity; ~7–20% BM).[10] It seems logical that research adhering to these methods typically reports similar performance outcomes for resisted versus unresisted training protocols, albeit with a consensus in favor of the use of resisted sled training.[10] While lighter loading is not inherently bad and may play a part in the development of horizontal force at high velocities, the results from this study show that these loads may not provide an effective stimulus for maximizing horizontal power production. For example, even the lowest case of optimal loading in this study (69% BM) greatly exceeds these guidelines. Results from research measuring the single-step kinetics of heavier loading protocols (~20–43% BM)[29,30] during the acceleration phase would seem to support this assertion. It should be noted that all loads used were considered to substantially affect sprinting technique (although this was not measured).[27,28] Consequently, we suggest that the methods used in this study be considered as a training stimulus for the development of horizontal power that may reflect improvements in the physical and technical capacities underlying sprinting performance.[3,31]

P_{max} in a multiple-trial method is computed from the peak of the polynomial regression obtained from several sprint trials against different loads and should not be dissimilar to the instantaneous value obtained during a single-sprint trial.[5] Consequently, P_{max} determined in this study corresponds to the instantaneous maximum power of the athletes, developed for a very short duration during the first 1 to 2 seconds of a sprint acceleration phase,[18] not only the P_{max} that the athlete can develop at maximum resisted velocity. As such, according to theories underlying the Fv relationship, training in optimal conditions for power (ie, equal emphasis on force and velocity) should equally increase force and velocity capacities and resultant power production during sprint acceleration.[2,7] In practice, this may not be the case, as this theoretical perspective does not consider disparate capacities specific to either end of the force–velocity capacity (eg, elastic components), as well as complexities involved in changing technique.[1] Applying this principle to our results, given that the Fv relationship developed from multiple trials represents the span of the athlete's ability to produce force and velocity with impeding resistance (similarly to that during an unloaded sprint[3,4,31]), we speculate that training in this manner may present positive changes in unloaded sprinting-acceleration performance. However, we hypothesize that training in this manner may disproportionately emphasize early acceleration ability and either maintain or present lesser increases in late acceleration or v_0. In any case, further research and testing are necessary to examine these assertions and to determine whether positive, worthwhile, and timely adaptations are observed in varying athlete subsets.

Our results suggest that FvP profiles and optimal loading conditions can be accurately and reliably profiled during multiple overground sprints. The simple and accessible technologies used in this protocol strengthen its usability in practice and research. Further research is necessary to determine whether these loading magnitudes and ranges are observed in other athlete groups. In particular, acceleration- and force-dominant populations (eg, rugby code athletes) would offer an interesting juxtaposition to the velocity-dominant sprinters profiled in this study. Finally, future studies should assess the longitudinal effects of optimally loaded sprints on horizontal power, sprinting performance, and sprinting technique.

Limitations

All athletes wore their standard training attire for maximal sprinting to best represent their "maximal" sprinting effort. Consequently, recreational athletes wore trainers, and sprinters wore sprinting spikes. While it is acknowledged that this may have affected the ability to apply force through increased friction (or other factors with regard to the specialist design of sprinting spikes), the degree to which this influenced the results is expected to be minimal and acceptable due to better representing maximal conditions for the athlete group. Progressive, nonrandomized application of loading was used in this procedure as per previous studies,[6,12] which may have affected the results observed reminiscent of potentiation or fatigue. Nonrandomized loading was selected for 2 primary reasons: Measureable increments were necessary to determine the point at which to cease testing (as per previous research), and pilot testing revealed that performance was often variable without athletes being able to cue the resistance from the protocol directly preceding it.

Practical Implications

- The optimal loading conditions for maximal power are much greater than currently used in the literature (individual L_{opt} of 69–96% vs <43% BM and v_{opt} of 48–52% vs <30% v_{hmax} decrement), indicating that practitioners and researchers should reconsider the guidelines with which they implement sled sprints and similar resisted-sprint modalities.
- Practically, these techniques may be integrated into training by having an athlete build to maximal resisted velocity (under L_{opt}, or simply a load that generates an ~50% decrement in unloaded sprinting velocity) and maintain maximum effort—enabling extended work to be performed in conditions maximizing power (eg, ~5 s, or 10–20 m).
- The wide range in athlete optimal loading characteristics observed in this study indicates the need for individualized training zones in both recreational and highly trained sprint athletes.

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