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Uphill sprinting load– and force–velocity profiling: Assessment and potential applications

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ABSTRACT

This study aimed to quantify the validity and reliability of load–velocity (LV) relationship of hill sprinting using a range of different hill gradients and to describe the effect of hill gradient on sprint performance. Twenty-four collegiate-level athletes performed a series of maximal sprints on either flat terrain or hills of gradients 5.2, 8.8 and 17.6%. Velocity–time curves were recorded using a radar device. LV relationships were established using the maximal velocity achieved in each sprinting condition, whilst force–velocity–power (FVP) profiles were established using only the flat terrain sprint. LV profiles were shown to be valid (R^2 = 0.99) and reliable (TE < 4.4%). For every 1-degree increase in slope, subjects' velocity decreased by 1.7 ± 0.1% on average. All the slopes used represented low resistance relative to the entire LV spectrum (<25% velocity loss). Subjects who exhibited greater horizontal force output at higher velocities on flat terrain were most affected by the gradient of the hill. Hills of gradients up to 17.6% do not provide sufficient resistance to optimize power development. However, such hills could be used to develop late-stage technical ability, due to the prolonged horizontally oriented body position that occurs as subjects attempt to overcome the acceleration due to gravity.

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Introduction

Sprint ability is a key performance indicator for many team sports. This capacity has been shown to distinguish playing levels in team-sport athletes; for example, soccer (Devismes et al., 2019). Therefore, improving an athlete's sprint ability is a high priority among sport coaches and performance staff. Sprint performance can be primarily explained by its underpinning mechanical components, including horizontal force, power, and velocity (Samozino et al., 2016). An understanding of these constructs has been shown to assist in the development of specific and individualized training programmes, optimizing adaptation and improving overall performance (Morin & Samozino, 2016). The recent development of a simple field-based assessment of the mechanical profile of sprint acceleration (Morin et al., 2019; Samozino et al., 2016) has provided coaches and practitioners with the information to design individualized training programs that was previously restricted to expensive laboratory-based settings. It is now understood that sprint acceleration performance can be improved by maximizing horizontal power output (Cross, Brughelli et al., 2017). Given that "power" is conceptually the change in mechanical work over time, which is equivalent to the product of both force and velocity in a given direction, the development of both characteristics is important for increasing external power output expressed in the main direction of motion during sprinting.

During multi-segmental exercises such as jumping and running, force production capacities linearly decrease with movement velocity (Morin & Samozino, 2016). The force and velocity intercepts of this relationship represent the maximal theoretical force (F0; maximal theoretical force the system can produce at zero velocity) and velocity (V0; maximal theoretical velocity until which the system can produce force) of the athlete. Power output can then be calculated at any point across this relationship as a product of both force and velocity. By assessing the force–velocity relationship at a range of intensities, practitioners can calculate the combination of these metrics at which maximal power (P_{max}) is achieved, typically termed optimal. Although P_{max} itself is useful for quantifying performance in a desired task, the conditions at which P_{max} is achieved also represent optimal training conditions for power development (Cross, Brughelli et al., 2017; Dorel et al., 2010) and occurs at approximately 50% of maximal velocity (optimum velocity; V_{opt}).

To expose athletes to training conditions at which power exposure (especially effort time close to P_{max}) is optimized (i.e., V_{opt}), high levels of external resistance are required (Cross, Brughelli et al., 2017). Specific to sprint training, this notion differs from traditional resisted sprinting recommendations, whereby minimal resistance was recommended as to not disrupt running kinematics (Lockie et al., 2003). Nonetheless, heavy sleds represent a training methodology, whereby individualized load–velocity relationships can be established, and a load corresponding to the speed at which V_{opt} occurs can be calculated,

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a method which has been shown to optimize training adaptations without adverse effects on unresisted sprint form (Lahti et al., 2020). However, standardizing the external load provided by the sled can be challenging due to changes in environmental conditions (weather, running surface, etc.) significantly affecting the resistance provided by a certain external load (Linthorne & Cooper, 2013), and therefore, practitioners are encouraged to use velocity decrements (i.e., percentage of maximal unloaded sprint speed) to standardize resistance loading (Cahill et al., 2019). Additionally, implementing a heavy sled protocol with large squads and limited equipment may be difficult, and therefore, other training methodologies may be sought after.

Hill sprints are commonly prescribed in athletic preparation programs as a means of improving sprint ability by overloading the hip and knee extensor muscles (Cronin & Hansen, 2006). Like heavy sleds, it may be suggested that hills can be used as a form of external resistance (i.e., in the form of a gravitational overload), with the intention of optimizing mechanical power output in the direction of motion and orienting that power in a horizontal direction. An early study (Paradisis & Cooke, 2001) reported a 3% loss of peak running speed (established as the highest average speed of the centre of mass over the duration of one stride cycle using 250 Hz camera) during sprinting on a 3° (5.2%) hill, which is a relatively small change considering the entire load–velocity spectrum. Given that the maximal mechanical power output zone of the velocity–power curve corresponds to 50% of maximal velocity (Cross, Brughelli et al., 2017; Dorel et al., 2010), these findings would suggest that significantly steeper hills may be required to provide mechanical conditions for maximizing power development. Therefore, a greater understanding of the impact of hill gradient on sprint performance may reveal additional information about where such activity falls on the force-velocity spectrum and therefore allow coaches to be more targeted in their approach when prescribing sprint training. Therefore, the aims of this study were to: 1) determine whether hills of various grades can be used to establish a valid and reliable equivalent load–velocity profile during sprinting and 2) to describe the effect of hill gradient on sprint performance relative to the entire load–velocity relationship.

Methods

Participants

Twenty-four Division 1 athletes were recruited for this study (males: n = 10, age = 21 ± 1 yrs, height = 1.86 ± 0.10 m, body mass = 86.7 ± 11.7 kg; females: n = 14, age = 21 ± 2 yrs, height = 1.81 ± 0.10 m, body mass = 74.1 ± 8.1 kg). The cohort was representative of several sports, including volleyball, basketball, track and field and tennis. All athletes possessed at least 1 year of sprint training experience, were free from injury and were familiarized with all procedures reported. Athletes gave their written informed consent to participate in this study, and the study was approved by the institution's ethical board.

Design

This study aimed to determine whether a valid load–velocity relationship exists between sprint peak velocity and the magnitude of hill gradient, including 0, 5.2, 8.8 and 17.6%. In addition to the initial testing protocol, a subgroup of 9 athletes returned after a period of 7 days and repeated the below protocol to determine intersession reliability. All testing was completed outdoors (temperature 30–34°C) on an artificial turf surface, in normal training attire, in still conditions.

Methodology

All athletes presented for testing in a rested and hydrated state in their typical training attire (i.e., standard athletic footwear). A standardized ~30 min warm up including dynamic movements, technical drills and a series of submaximal ~30 m sprints (increasing in intensity up to ~90% of self-selected maximal velocity) was performed. Players were afforded a 5-min passive rest period prior to testing, while the testing procedures were explained to them. The sprint protocol involved two maximal sprints on each of the three different hill gradients (5.2, 8.7 and 17.6%) and three sprints on flat terrain in a randomized order, for a total of 9 sprints, separated by 2–3 minutes of recovery. The 5.2 and 8.7% slopes used in this study were purpose built previously with the goal of developing shorter and longer acceleration abilities, respectively (Cronin & Hansen, 2006). The steepest of the three hills (17.6%) was originally built as a backdrop and exit for the other two hills but was used in the present study due to its steeper slope and similar surface and condition to the other two hills. Although a larger spectrum of gradients was preferred, it was a decision of the research group that other hills of different surface types (i.e., asphalt or grass) would compromise the integrity of the study.

For each trial, the athlete would step up to a marked line and take a two-point split stance of self-selected width. Athletes were instructed to sprint maximally for 30 m. Velocity–time data were recorded using a radar device (Stalker ATS II, TX, USA) sampling at 46.9 Hz, set on a tripod at a height approximate to the athletes' centre of mass (~1 m) and positioned ~5 m behind the athlete's starting point on the same slope that the athlete was sprinting on, so that velocity measurements were taken parallel to the slope of the ground. Each sprint was recorded to a laptop computer and was trimmed and tagged using the manufacturer's proprietary software prior to further analysis.

Force–velocity profiling

All data processing was performed using custom-written software (R Studio, version 1.3.1093). For sprints performed on flat terrain, force–velocity–power (FVP) profiles were calculated using methods described previously (Samozino et al., 2016). Briefly, this technique uses measured position-time data and fits a mono-exponential equation to estimate the instantaneous horizontal velocity throughout the entire sprint, using the least-squares regression method. Through derivation of the modelled velocity–time curve, instantaneous horizontal force can be estimated, which has been shown to exhibit

Table 1. Definition and practical interpretation of the main variables of interest when using force–velocity–power profiling in sprinting (adapted with permission, (Samozino et al., 2016)).

Profiling Variable	Definition and Computation
F0 ($N \cdot kg^{-1}$)	Theoretical maximal horizontal force production as extrapolated from the linear sprint FV relationship; *y*-intercept of the linear FV relationship.
V0 ($m \cdot s^{-1}$)	Theoretical maximal running velocity as extrapolated from the linear sprint FV relationship; *x*–intercept of the linear FV relationship.
P_{max} ($W \cdot kg^{-1}$)	Maximal mechanical power output in the horizontal direction, computed as $Pmax = F0 \times V0/4$, or as the apex of the PV 2nd-degree polynomial relationship.
FVslope	Index of the athlete's individual balance between force and velocity capabilities. The steeper the slope, the more negative its value, the more "force-oriented" the FV profile, and vice versa.
RF (%)	Direct measurement of the proportion of the total force production that is directed in the forward direction of motion, i.e., the mechanical effectiveness of force application of the athlete. The higher the value, the more important the part of the total force output directed forward.
RF_{max} (%)	Maximal value of *RF*, computed as maximal value of *RF* for sprint times >0.3 s.
DRF	Rate of decrease in *RF* with increasing velocity during sprint acceleration, computed as the slope of the linear *RF*–V relationship.

considerable validity (standard error of the estimate [SEE] = 39.9 N ± 13.3 N, $r = 0.978$, $p < 0.0001$) when compared to the gold standard force plate method (Morin et al., 2019; Samozino et al., 2016). In addition, through integration of the modelled horizontal force and velocity data, a range of biomechanical variables can be estimated, including horizontal power, or mechanical effectiveness of force application, providing a greater understanding of the underlying mechanical determinants of sprint acceleration performance, or the FVP profile. A description of each of these variables is found in Table 1.

Load–velocity profiling

To determine the relationship between hill incline and sprint performance (load-velocity; LV), maximal sprint velocity achieved during each of the hill sprints was recorded using the radar device (Stalker ATS II, TX, USA), using the same methods outlined for the FVP profile. For the purposes of these analysis, only maximal sprint velocity was recorded from each trial. Linear relationships between sprint velocity achieved and gradient of the hill within the four sprinting conditions (0, 5.2, 8.7 and 17.6%) were assessed as the LV profile. Specifically, the theoretical load at zero velocity (L0) was calculated as the x–intercept of the LV relationship, whilst the slope of that relationship (i.e., LV slope) represents the rate of decrease in velocity per unit of increased external resistance.

Statistical analysis

All statistical analyses were completed in R Studio (version 1.3.1093). Descriptive statistics are presented as mean ± SD unless otherwise stated. To determine the appropriateness of establishing LV relationships using hills of various inclines, relationships between sprint gradient and velocity achieved during the sprint were assessed using a linear mixed model using the *lme4* package (Bates et al., 2015) with 100 × natural logarithm of maximal velocity as the dependent variable and incline and gender as fixed effects. Individual athlete identification was included as a random effect to account for repeated measures. Individual slope and intercept values were specified in the linear mixed model. The fit and performance of the linear mixed model was quantified by assessing the residual versus fitted plots and also by calculating the conditional R^2 value using the *MuMIn* package (Harrison et al., 2018). Individual model coefficients were extracted from the model for further analysis. These modelled data were selected in preference to raw values to overcome the potential for sex to falsely inflate the results of correlational analyses. Relationships with the mechanical properties of sprinting on flat terrain were assessed using Pearson's correlation coefficients and interpreted according to Hopkins as almost perfect (>0.9), very large (>0.7), large (>0.5), moderate (>0.3), small (>0.1), or trivial (<0.1) using a magnitude-based inference network (Hopkins et al., 2009). Effects were considered real if the likelihood of the true effect exceeded 75% and were considered as *likely* (>75%), *very likely* (95%) and *almost certainly* (>99.5%) (Hopkins et al., 2009). Inter-session reliability of LV profiles was determined using the typical error (TE), both in raw units and as a percentage (TE%). Confidence levels were set at 90%.

Results

Descriptive statistics of baseline FVP and LV profiles of sprint acceleration are found in Table 2. During hill sprinting, subjects reached 92 ± 2%, 87 ± 2% and 75 ± 3% of their maximal flat terrain running velocity for hills of 5.2, 8.7 and 17.6%, respectively. An almost perfect relationship was assessed between the velocity achieved and gradient of the hill for ($R^2 = 0.99$). The slope of the relationship between hill gradient and maximal velocity (as a percentage of the individual's max velocity) was −1.7 ± 0.1%. This slope represents the percentage decrement in velocity for each 1% increase in slope incline. Figure 1 demonstrates the mean ± SD decrease in maximal speed as the incline of hill increases. Figure 2

Table 2. Descriptive statistics (mean ± SD) for individual force–velocity–power (FVP) and load–velocity (LV) profiles for collegiate level athletes.

Profile	Variable	Male (n = 10)	Female (n = 14)	Pooled (n = 24)
FVP	Maximal Velocity ($m \cdot s^{-1}$)	8.43 ± 0.67	7.46 ± 0.46	7.81 ± 0.75
	V0 ($m \cdot s^{-1}$)	8.78 ± 0.75	7.74 ± 0.52	8.12 ± 0.83
	FVslope ($N \cdot kg^{-1}/m \cdot s^{-1}$)	−0.82 ± 0.11	−0.84 ± 0.1	−0.83 ± 0.1
	F0 ($N \cdot kg^{-1}$)	7.2 ± 0.97	6.47 ± 0.58	6.74 ± 0.83
	P_{max} ($W.kg^{-1}$)	15.9 ± 2.8	12.5 ± 1.3	13.8 ± 2.7
	RF_{max} (%)	43.2 ± 3.6	39.3 ± 1.8	40.7 ± 3.3
	DRF (%)	−7.7 ± 1	−8 ± 0.9	−7.9 ± 0.9
LV	L0 (%)	73.9 ± 3.7	67.6 ± 3.4	70.2 ± 4.7
	LVslope ($m \cdot s^{-1}/\%$)	−0.11 ± 0.01	−0.11 ± 0.01	−0.11 ± 0.01
	L @ Vopt (%)	36.9 ± 1.9	33.8 ± 1.7	35.1 ± 2.3

V0 = maximal theoretical velocity; FVslope = slope of the force-velocity relationship; F0 = maximal theoretical force; P_{max} = maximal theoretical relative power; RF_{max} = maximal ratio of force horizontal:vertical force; DRF = decrease in ratio of force, L0 = maximal theoretical load at zero velocity; LVslope = slope of the load-velocity relationship; L @ Vopt = load at optimum velocity.

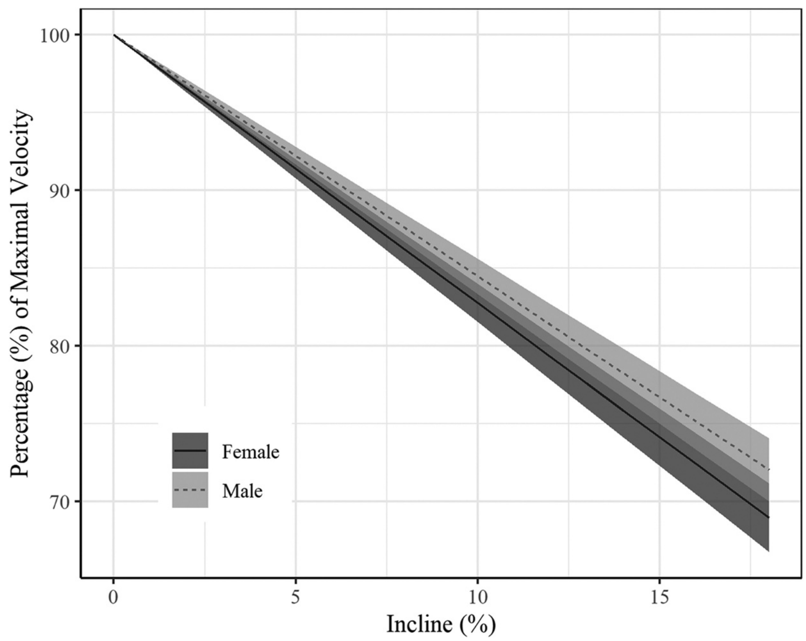

Figure 1. Load–velocity profile during hill sprinting of collegiate-level athletes. Trendline represents the average profile (± SD) for males (n = 10) and females (n = 14), respectively.

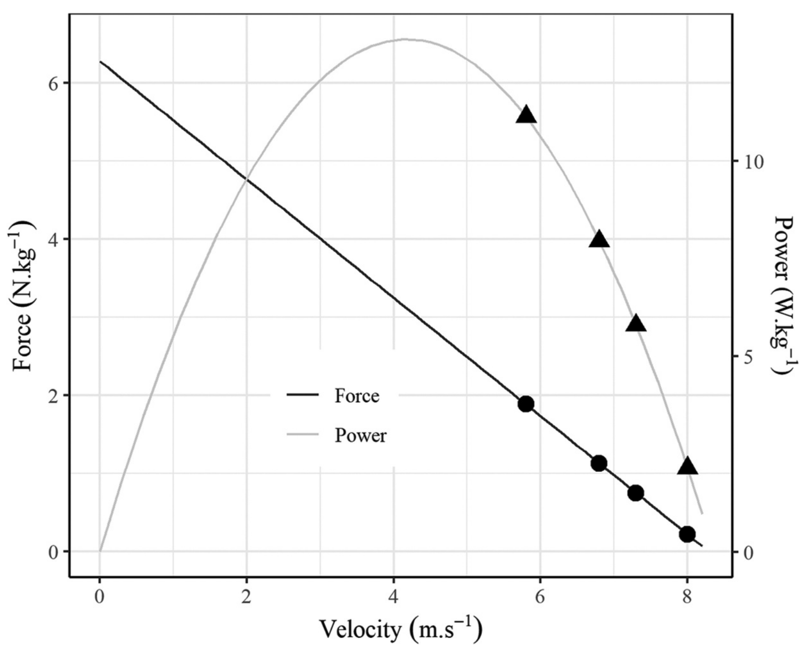

Figure 2. Example of one athlete's force–velocity–power profile measured during sprint on flat terrain (trendlines representing force–velocity and power–velocity relationships, respectively). Points on each line represent the velocity achieved during the flat sprint and each of the three different hill conditions, demonstrating that the gradients assessed during this study represented the velocity end of the force–velocity relationship.

illustrates an example of one athlete's force–velocity profile for the flat sprint, which has been overlaid with markers indicating the velocity achieved during each of the four sprint conditions. Load at theoretical optimum velocity (L @ V_{opt}) was 36.9 ± 1.9%, 33.8 ± 1.7% and 35.1 ± 2.3% for males, females and the pooled groups, respectively.

Sprint maximal velocity was shown to be reliable across the four different sprint conditions (TE = 0.08 to 0.13 m·s^{-1}; 1.2 to 1.8%) between sessions (Table 3). L0, representing the theoretical load at zero velocity, was similarly reliable (TE = 0.74; 0.53 to 1.26°; 1.8; 1.3 to 3.1%). The slope of the LV relationship was the least reliable of the LV variables, but still was considered acceptable (TE = 0.01; 0.01 to 0.01; 4.4; 3.2 to 7.7%).

Relationships between FVP and LV variables are presented in Table 4. L0 shared large to very large, positive relationships with maximal velocity, V0, F0, P_{max} and RF_{max} (r = 0.54 to 0.79) and small to moderate, negative relationships with FVslope and DRF (r = −0.34 to −0.27). There were large to very large, negative correlations between LV slope and maximal velocity, V0, FV slope and DRF

Table 3. Reliability statistics (± 90% confidence intervals) for individual load–velocity measures during hill sprinting for collegiate level athletes.

Variable	Trial 1	Trial 2	TE	TE (%)
V @ 0%	8.15 ± 0.74	8.03 ± 0.79	0.13; 0.09 to 0.22	1.8; 1.3 to 3.1%
V @ 5.2%	7.50 ± 0.72	7.37 ± 0.70	0.09; 0.07 to 0.16	1.3; 0.9 to 2.2%
V @ 8.8%	7.11 ± 0.72	6.98 ± 0.71	0.08; 0.06 to 0.14	1.2; 0.8 to 2.0%
V @ 17.6%	6.01 ± 0.68	6.11 ± 0.67	0.09; 0.07 to 0.16	1.6; 1.2 to 2.8%
LV Slope	−0.19 ± 0.02	−0.21 ± 0.02	0.01; 0.01 to 0.01	4.4; 3.2 to 7.7%
L0	93.3 ± 8.2	90.99 ± 7.5	0.74; 0.53 to 1.26	1.8; 1.3 to 3.1%

TE = typical error; V = velocity ($m{\cdot}s^{-1}$); LV slope = slope of the load–velocity relationship; L0 = theoretical load (gradient; %) at zero velocity.

Table 4. Relationship between LV variables measured during hill sprinting and mechanical properties of sprinting on flat terrain. Data are presented as mean; 90% confidence intervals.

FVP Variable	L0		LV Slope	
Maximal velocity ($m{\cdot}s^{-1}$)	0.58; 0.3 to 0.77	***	−0.73; −0.86 to −0.52	***
V0 ($m{\cdot}s^{-1}$)	0.54; 0.24 to 0.75	**	−0.76; −0.88 to −0.57	***
FVslope	−0.34; −0.61 to 0.01	*	−0.64; −0.81 to −0.38	***
F0 ($N{\cdot}kg^{-1}$)	0.76; 0.57 to 0.88	***	0.02; −0.33 to 0.36	
P_{max} ($W{\cdot}kg^{-1}$)	0.77; 0.59 to 0.88	***	−0.4; −0.65 to −0.06	*
RF_{max}	0.79; 0.61 to 0.89	***	−0.31; −0.59 to 0.03	*
DRF	−0.27; −0.56 to 0.09	*	−0.69; −0.84 to −0.46	***

V0 = maximal theoretical velocity; FVslope = slope of the force-velocity relationship; F0 = maximal theoretical force; P_{max} = maximal theoretical relative power; RF_{max} = maximal ratio of force horizontal:vertical force; DRF = decrease in ratio of force; * = *likely*; ** = *very likely*; *** = *almost certainly*.

(r = −0.76 to −0.64) and small to moderate, negative relationships between LV slope and P_{max} and RF_{max} (r = −0.41 to −0.33).

Discussion

In recent years, heavy resisted sled towing has become a popular method for developing early acceleration mechanical force, power and more horizontally oriented application of the ground reaction force amongst athletes. Load–velocity profiling represents a technique for optimizing such training. However, to the authors' knowledge, this is the first study to investigate LV relationships during hill sprinting using a multiple-trial approach. Overall, our findings suggest that the relationships between hill gradient and maximal sprint velocity achieved can be fitted accurately with linear equations, in line with those relationships observed using sleds on flat terrain (Cahill et al., 2019; Cross, Brughelli et al., 2017). However, within the current study the spectrum of hill gradients available (i.e., 0–17.6%) represented a relatively small range in relation to the entire velocity spectrum, covering ~25% (from fastest to slowest sprint) of that spectrum on average (Figure 2). Similar studies have used a much wider range of loads to quantify the LV profile accurately in exercises such as sled towing (Cahill et al., 2019; Cross, Brughelli et al., 2017), bench press (Loturco et al., 2017) and squatting (Banyard et al., 2018). Whilst the narrow range utilized in the present study is a limitation, the almost perfect fit of the load–velocity relationships (R^2 = 0.99; 0.99 to 1), along with the high test-retest reliability of the method (TE% = 1.2 to 4.4%), suggest that this range was appropriate for determining an accurate LV relationship in this cohort.

Using information derived from a LV profile, coaches and practitioners can individualize training prescription for the development of horizontal power output. To optimize power output, it is recommended that the load and/or velocity at which peak power occurs is prescribed (Jimenez-Reyes et al., 2019). When towing sleds as resistance, the load prescribed may change from session to session due to differences in the effect of friction of the sled (Linthorne & Cooper, 2013), and therefore, velocity loss can be recommended to standardize loads across athletes (Cahill et al., 2019). Using the slope of the load–velocity relationship (LV slope) in the present study, it can be seen that on average, for every 1% of incline, a velocity loss of ~1.7% occurs. This value varied slightly between athletes (0.1%) indicating that athletes were affected slightly differently by the slope of the hill. Theoretically, this would suggest that prescribing the same gradient hill to a group of athletes may be providing a different stimulus to each athlete, and these differences would be magnified as the gradient of the hill increases and therefore establishing individualized LV profiles may be necessary. However, the assessment of individualized profiles may not be practical, as it requires a range of slopes of different magnitudes like those described in this study. Given that hills of lesser magnitude are more likely to be available to practitioners and these hills would therefore exhibit smaller absolute error between athletes, it may be that generalized LV profiles are appropriate for prescribing hill-resisted sprints for groups in such conditions, provided the associated error is understood.

In practical terms, practitioners can use the slope of the LV relationship to understand the expected velocity loss during maximal sprints on a given hill, provided the incline of the hill is known, and therefore where on the FV spectrum that exercise will fall. However, given that peak power occurs at approximately 50% of V0 (i.e., V_{opt}), the athletes in this study would require hill gradient of 35 ± 2% to target that capacity. Previous analysis of the effect the such gradients (30%) have only be examined using treadmill-based constant speed running (4.5 m·s^{-1}) (Swanson & Caldwell, 2000) suggesting that that hills of such gradients are far from common. As a result, using hills to target maximal power seems impractical (except if adding sled load during uphill sprints), and it may be that heavily loaded sled towing and robotic resistance devices remain the best way to target the mechanical conditions for optimal horizontal power output exposure during sprint training.

A secondary aim of the present study was to assess the relationship between the LV profile, measured using hill sprints, and the mechanical properties of sprinting on flat terrain (FVP profile). The slope of the LV relationship was strongly and negatively correlated with maximal velocity, V0, FV slope and DRF. Each of these metrics share the similar theme of a "force output at high velocity" component, suggesting that athletes who were faster and were able to produce horizontal force for longer during the flat-terrain sprint were the same athletes who were most negatively impacted by the increase in hill gradients. These findings are in line with others (Jaskólska et al., 1998), where velocity-dominant athletes outperformed their slower counterparts during sprints with low resistance, but differences were less clear at heavier loads. These authors attributed this difference to the varying muscle architecture between groups, suggesting faster players exhibited a greater proportion of fast-twitch muscle fibres. It may also be the case that during both heavily loaded sprints and unloaded uphill sprints, athletes are restricted in their ability to increase stride length due to the forward inclined body position relative to the ground. In contrast, players who were more proficient at the start of the sprint as evidenced by superior F0, P_{max} and RF_{max} values, were also the athletes who were least affected by the increasing slope. Taken together, these results indicate that hill sprints may provide a different training stimulus compared to sprints on flat terrain, likely due to the longer duration in an acceleration-like body position, though this requires support from further training studies.

Overall, the findings of this study suggest that although a linear relationship exists between the magnitude of the slope of a hill and the velocity attainable on that hill, the relatively small velocity loss experienced on typical hills may not be enough to target mechanical power development. However, hill sprinting may result in other favourable training adaptations separate from horizontal power production. Traditionally, loads that induce minimal velocity loss (7.5–15.5%) are prescribed, with the intention of minimizing kinematic alterations compared to unloaded sprinting (Petrakos et al., 2016). This notion has recently been contested, with no significant changes in sprint kinematics observed after a 9-week training intervention, including resisted sprints with 50 or 60% velocity decrement (Lahti et al., 2020). As mechanical power development was the goal and main outcome of that programme, it is encouraging that no associated changes in kinematics were observed. However, mechanical power development forms only one part of a well-rounded individually designed speed training program (Gamble, 2012) and sprinting with resistance that induces smaller velocity decrements (i.e., <50% velocity loss) may be useful for reasons other than purely power development, depending on the individual FV and LV orientation of the athletes (Morin & Samozino, 2016). For example, the hill gradients used in the present study could be used to develop late-stage acceleration technical ability, due to the prolonged horizontally oriented body angle (relative to the ground) that occurs as athletes attempt to overcome the acceleration due to gravity (Paradisis & Cooke, 2001). Although less time is spent in acceleration during resisted sprinting (Cross, Brughelli et al., 2017), the prolonged contact times and increased leg extensor activity that occurs during uphill running at constant speed (Swanson & Caldwell, 2000) suggests that hills can be used to train acceleration abilities. In addition, a unique benefit of hill sprinting is that the resistance provided by the hill remains constant throughout (provided the hill is of constant gradient), which is not always the case in sled towing conditions (due to the changing effect of friction at different velocities) (Cross, Tinwala et al., 2017). Nonetheless, these suggestions remain speculative and require further kinematic analysis and training intervention studies to investigate.

Limitations

- Due to obvious logistical difficulties, only three different hill gradients were assessed, and these gradients represent only a small fraction of the entire velocity spectrum amongst this cohort.
- The analysis of kinematic variables such as stride length and contact time may have revealed more insights into the differences between hill gradients, but this was outside the scope of the present study.

Practical applications

- From a mechanical power standpoint, hill sprinting may not impose a great enough velocity loss (and in turn overload) to optimize power output development in trained athletes.
- Due to the longer time spent at low velocities, hill sprints may reflect an ideal training stimulus for developing horizontal force output and the ability to direct that force at an angle that is more inclined to the support surface.
- Although this study was able to determine the effectiveness of hills for eliciting a maximal power stimulus, further kinematic analyses may reveal further information about the changes that may occur either during or as a result of this type of training.

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