FORCE-VELOCITY PROFILING IN SLED-RESISTED SPRINT RUNNING: DETERMINING THE OPTIMAL CONDITIONS FOR MAXIMIZING POWER

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ABSTRACT

The measurement of power-velocity and force-velocity relationships offers valuable insight into athletic capabilities. The qualities underlying maximum power (i.e. optimal loading conditions) are of particular interest in individualized training prescription and the enhanced development of explosive performance. While research has examined these themes using cycle ergometers and specialized treadmills, the conditions for optimal loading during over-ground sprint running have not been quantified. This thesis aimed to assess whether force-velocity-power relationships and optimal loading conditions could be profiled using a sled-resisted multiple-trial method overground, if these characteristics differentiate between recreational athletes and highly-trained sprinters, and whether conditions for optimal loading could be determined from a single sprint. Consequently, this required understanding of the friction characteristics underlying sled-resisted sprint kinetics. Chapter 3 presents a method of assessing these characteristics by dragging an instrumented sled at varying velocities and masses to find the conversion of normal force to friction force (coefficient of friction). Methods were reliable (intraclass correlation [ICC]>0.99; coefficient of variation [CV]<4.3%) and showed the coefficient of friction was dependent on sled towing velocity, rather than normal load. The 'coefficient of friction-velocity' relationship was plotted by a 2nd order polynomial regression (R^2=0.999; P<0.001), with the subsequent equation presented for application in sled-resisted sprinting. Chapter 4 implements these findings, using multiple trials (6-7) of sled-resisted sprints to generate individual force-velocity and power-velocity relationships for recreational athletes (N=12) and sprinters (N=15). Data were very well fitted with linear and quadratic equations, respectively (R^2=0.977-0.997; P<0.001), with all associated variables reliable (effect size [ES]=0.05-0.50; ICC=0.73-0.97; CV=1.0-5.4%). The normal loads that maximized power (mean±SD) were 78±6 and 82±8% of body-mass, representing an optimal force of 279±46 and 283±32 N at 4.19±0.19 and 4.90±0.18 m.s^{-1}, for recreational and sprint athletes respectively. Sprinters demonstrated greater absolute and relative maximal power (17.2-26.5%; ES=0.97-2.13; P<0.02; *likely*), with much greater velocity production (maximum theoretical velocity, 16.8%; ES=3.66; P<0.001; *most likely*). Optimal force and normal loading did not clearly differentiate between groups (unclear and *likely* small differences; P>0.05), and sprinters developed maximal power at much higher velocities (16.9%; ES=3.73; P<0.001; *most likely*). The optimal loading conditions for

maximizing power appear individualized (range=69-96% of body-mass), and represent much greater resistance than current guidelines. Chapter 5 investigated the ability of a single sprint to predict optimal sled loading, using identical methods to Chapter 4 and a recently validated profiling technique using a single unloaded sprint. Power and maximal force were strongly correlated (r=0.71-0.86), albeit with moderate to large error scores (standardized typical error estimate [TEE]=0.53-0.71). Similar trends were observed in relative and absolute optimal force (r=0.50-0.72; TEE=0.71-0.88), with estimated optimal normal loading practically incomparable (bias=0.78-5.42 kg; r=0.70; TEE=0.73). However optimal velocity, and associated maximal velocity, were well matched between the methods (r=0.99; bias=0.4-1.4% or 0.00-0.04 m.s^{-1}; TEE=0.12); highlighting a single sprint could conceivably be used to calculate the velocity for maximizing horizontal power in sled sprinting. Given the prevalence of resisted sprinting, practitioners and researchers should consider adopting these methods for individualized prescription of training loads for improved horizontal power and subsequent sprinting performance.

LIST OF FIGURES

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ATTESTATION OF AUTHORSHIP

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning.

Chapters 2 through 5 of this thesis represent four separate papers that have either been published, have been submitted, or will be submitted to peer-reviewed journals for publication. My contribution to these works, and that of the various co-authors, are outlined on the following pages and have been approved the inclusion of the joint work in the body of this masters' thesis.

Signed …………………………………………

Date   14 April 2016
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CANDIDATE CONTRIBUTIONS TO CO-AUTHORED PUBLICATIONS

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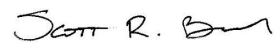
Pierre Samozino   Farhan Tinwala   Seth Lenetsky   Scott R. Brown

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ETHICAL APPROVAL

Ethical approval for this research was granted by the Auckland University of Technology Ethics Committee (AUTEC; #15/61) originally on 13 April 2016, with minor amendments approved on 20 October 2016 (see Appendix 1).

LIST OF COMMON ABBREVIATIONS

Fv	Force-velocity relationship; Linear (least-squares) regression between force and velocity
Pv	Power-velocity relationship; Parabolic (2nd order polynomial) relationship between power and velocity
FvP	Force-velocity-power relationship; Colloquial reference to the combination of mechanical qualities that comprise the relationships between force-velocity and power-velocity
P_{max}	Maximum power; Instantaneous peak of the parabolic power-velocity relationship
$P_{max}2$	Maximum power (2); Maximal power, determined via the following validated equation: $(F_0 \cdot v_0)/4$
F_0	Maximum theoretical force; The maximal force production of the lower limbs theoretically possible in the absence of velocity, as extrapolated from the linear Fv relationship
v_0	Maximum theoretical velocity; The maximal velocity of the lower limbs theoretically possible in the absence of force, as extrapolated from the linear Fv relationship
S_{Fv}	Slope of the linear Fv relationship; Computed as $S_{Fv} = (-F_0/v_0)$
F_{opt}	Level of force occurring at P_{max}; Graphically, it represents the y-intercept of the point where the combination of force and velocity present the greatest power output, computed as $0.5 \cdot F_0$
v_{opt}	Optimal velocity for maximal power; Level of velocity occurring at P_{max}. Graphically, it represents the x-intercept of the point where the combination of force and velocity present the greatest power output, computed as $0.5 \cdot v_0$
L_{opt}	Optimal normal loading for maximal power; Level of normal loading occurring at P_{max}, determined from F_{opt} with consideration of factors attributing to its conversion (e.g. friction characteristics)
μ_k	Coefficient of friction; The conversion of normal force to friction force
F_n	Normal force; The vertically oriented loading in units of force
L_n	Normal mass; The vertically oriented loading in units of kilograms
F_f	Friction force; the resultant resistance provided as a result of the coefficient of friction, normal loading, and angle of pull
F_{aero}	Aerodynamic friction force
v_{max}	Maximum velocity
$\square_h$	Horizontal orientation; Used in variables with relation to sprinting
$\square_{corr}$	Corrected variable; Used reference to kinetic values that have been corrected with the addition of inertia during acceleration
$\square_{rev}$	Variable computed per revolution of a cyclic crank
$\square_{\square_{peak}}$	Variable computed at v_{max} (i.e. variable at 'peak')

T	Torque; Typically with respect to that exerted on the crank of a cycle ergometer
GRF	Ground reaction forces
GRF-z and F_V	Vertical ground reaction forces
α	Acceleration
χ	Horizontal orientation of centre of mass
BM	Body-mass
GPS	Global positioning system
1RM	1 repetition maximum
RF	Ratio of force; Computed as the ratio of the step-averaged horizontal component of the ground reaction force to the corresponding resultant force
D_{RF}	Decrement in ratio of force; Rate of decrease in RF with increasing speed during sprint acceleration, computed as the slope of the linear RF-v relationship
v_w	Wind velocity
k	Athlete's coefficient of aerodynamic friction
ρ	Air density
Af	Frontal area of the runner
Cd	Drag coefficient of ambient air
Pb	barometric pressure
T°	Air temperature
h	Athlete stature
θ	Angle of pull
h_t	Attachment height at athlete
c	Tether length
MBI	Magnitude based inferences
ES	Cohens effect size

CHAPTER 1

INTRODUCTION AND RATIONALE

Background and importance

Links between maximal power production and various athletic performance markers are accepted within the literature (e.g. Suchomel, Nimphius, & Stone, 2016). The mechanical capacity of a system for power production is commonly represented in the force-velocity (Fv) relationship, through which maximal power output may be enhanced by either increasing the ability to generate force output at low levels of velocity (i.e. force or strength dominated profile), maximize velocity production at low levels of force (i.e. speed or velocity dominated profile), or both capacities (Morin & Samozino, 2016). The assessment of horizontal power and mechanical relationships during sprint running, products of technical and physical capacity, allows specific and valuable insight into understanding sprinting performance (Clark & Weyand, 2015). Given that horizontal power and its associated determinants are highly related to acceleration ability during sprint running (Morin et al., 2015; Rabita et al., 2015), researchers have strived to develop methods of accurately assessing these characteristics in sport-specific movements; the aim being to better characterize athlete performance and give clarity to methods through which performance can be enhanced. Sprint running research is, however, relatively underdeveloped in this respect compared to other power dominant modalities such as jumping or sprint cycling (Driss & Vandewalle, 2013; Soriano, Jimenez-Reyes, Rhea, & Marin, 2015). As a result, there is a paucity of information regarding the assessment of power during sprint running, with little regarding its measurement during over-ground performance.

Power profiling, or the assessment of the mechanical capacities underlying power, provides insight into athlete characteristics and can provide valuable guidance for training prescription based on individual imbalances in the level of force or velocity at which maximal power is developed (Samozino, Rejc, Di Prampero, Belli, & Morin, 2012). The ability to produce maximal power during cyclic sprint exercise has been investigated using a range of technologies. Traditionally, researchers have quantified these abilities by plotting maximal

velocity output against a range of resistive loads during multiple trials on a cycle ergometer (multiple sprint method, Vandewalle, Peres, Heller, Panel, & Monod, 1987), with later research verifying that Fv relationships could be generated by plotting the velocity and force produced over each pedal stroke of a single maximal acceleration (single sprint method, Arsac, Belli, & Lacour, 1996; Lakomy, 1986; Martin, Wagner, & Coyle, 1997; Seck, Vandewalle, Decrops, & Monod, 1995). Importantly, both the single and multiple-trial methods show a linear decrement in increasing velocity with decreasing force, and parabolic power-load relationship and power-velocity (Pv) relationships. In these cases, the maximal power (P_{max}) ability can be quantified as the peak of the Pv relationship, and is commonly presented in research as a criterion of performance and athlete ability. Of further interest are the conditions underlying P_{max}, termed optimal force (F_{opt}) and optimal velocity (v_{opt}) (Sargeant, Dolan, & Young, 1984), due to the theory that training in these conditions may improve acute and longitudinal performance attributes (Wilson, Newton, Murphy, & Humphries, 1993). The potential of maximizing adaptions in power capacities highlights the value in assessing FvP and associated optimal loading conditions for subsequent training implementation, and coincidentally has received substantial interest in the literature (e.g. Cormie, McCaulley, Triplett, & McBride, 2007; Kawamori & Haff, 2004; Soriano et al., 2015; Wilson et al., 1993).

Power assessment in sprint running has commonly applied methods borrowed from the cycling literature to specialized sprint treadmills, implementing both multiple (Jaskólska, Goossens, Veenstra, Jaskólski, & Skinner, 1998, 1999) and single trial methods (Morin, Samozino, Bonnefoy, Edouard, & Belli, 2010) to determine mechanical variables. While markedly improved since their conception, there remain limitations inherent to treadmill based sprint profiling; namely, while undoubtedly more specific to on-field sprint running than their cycle based assessment counterparts, they remain dissimilar (acute alteration of kinematics and much lower velocity peaks 25-30%) (Morin et al., 2010). In answer to this, recent authors profiled these capabilities overground by using a method of transposing multiple sprint attempts from different starting distances behind a length of in-ground force plates into a single composite dataset and Fv relationship (Cavagna, 1975; Morin et al., 2015; Rabita et al., 2015; Samozino et al., 2016). Furthermore, a method has been validated to use simple distance and time data to model external horizontal force measures, and associated

force-velocity-power (FvP) relationships, during the entire acceleration phase of an over ground sprint (Samozino et al., 2016). Notably, in all of these cases, Fv and Pv relationships are accurately described by linear and parabolic relationships respectively, similarly to results from cycle based sprinting.

Similarly to cycling and jumping literature, the assessment of the FvP relationship in sprint running allows the calculation of optimal force and velocity for maximum power (Jaskólski, Veenstra, Goossens, Jaskólska, & Skinner, 1996), and while these variables have been reported in the literature (Cross et al. 2014), their application is somewhat limited. That is, while the variables associated with the optimal conditions for power production offer additional comparative analysis, their true value lies in training application to improve maximum power (Wilson et al., 1993). Specifically, using a training method to provide external resistance and decreased velocity to optimal levels (e.g. resisted sprinting) should positively influence an individual's ability to generate and/or orientate power in an effective manner longitudinally, and result in increased practical performance in sprinting specific activities. To date, with the exception of three studies (of varying quality and accuracy) indicating assessment of optimal loading is possible on sprint treadmill ergometry (Andre, Fry, & Lane, 2013; Jaskólska et al., 1999; Jaskólski et al., 1996), no research has provided specific optimal loading conditions for sprint running. Although literature has discussed 'optimal loading' for resisted sprint-training modalities (Cronin & Hansen, 2005; Jaafar et al., 2014; Rumpf, Lockie, Cronin, & Jalilvand, 2015; Wilson et al., 1993), research has typically recommended the use of resistance that does not significantly deviate from unloaded sprint running performance (Alcaraz, Palao, & Elvira, 2009; Lockie, Murphy, & Spinks, 2003). The fact that optimal conditions for power occur at approximately half of the maximum velocity attained in an unloaded sprint (e.g. Vandewalle, Peres, Heller, et al., 1987), and reviews of literature suggest that training using heavier versus lighter loading protocols may benefit sprint running performance to a greater degree (Petrakos, Morin, & Egan, 2016), appear to challenge these guidelines.

Profiling optimal loading during overground resisted sprinting would follow similar methodology to that of cycle and treadmill literature. That is, the use of resistance protocols (i.e. a loaded sled) to incrementally decrease subject velocity against increasing resistance, across multiple trials. Such a method would provide data on which to generate a composite

FvP profile, and allow the user to determine the conditions for maximal power, including a practical normal load for simple training implementation. Unfortunately, it is not known whether FvP relationships determined via this method follow linear and parabolic relationships, and therefore whether optimal force, velocity and normal loading can be accurately and reliably determined. Moreover, such an approach would need to consider the resistive force acting on the athlete (i.e. the horizontal or 'effective' force), rather than the commonly solely reported normal loading (Petrakos et al., 2016), to properly quantify the kinetics necessary for development of FvP relationships and optimal loading conditions.

Significance and purpose

FvP relationships can be measured during sprint running, where they provide valuable comparative information and guidance for individualized training prescription. While researchers have examined these relationships during both over-ground and treadmill based sprint efforts, there has been no effort to profile these abilities across multiple resisted efforts during over-ground sprint running. Furthermore, no attempts have been made to quantify optimal loading conditions for resisted sprinting based on kinetic data and FvP relationships. In order to better apply to practice, the modality used to provide resistance should be common in clinical and practical settings, easy to implement, and non-expensive. To this end, resisted sprint sleds were selected to provide the loading stimulus in this research. No studies have clearly presented a means for quantifying instantaneous kinetics during sled-resisted over-ground sprinting, therefore the first logical step is to determine a means by which friction force, and subsequent kinetic variables could be calculated for eventual application in profiling power during sprinting. This thesis serves to provide novel experimental data in these areas with specific application to over-ground sprinting analyses, enhancing the scientific understanding of the mechanical abilities characterising the body during sprint specific resisted exercise and providing a basis for future studies.

Thesis aims

The specific aims of this thesis were to:

1) Quantify friction characteristics and kinetics during sled towing, and provide a theoretical basis for application to sled sprinting;

2) Determine whether FvP relationships can be accurately profiled using a multiple-trial method during over-ground sled-resisted sprinting;

3) Quantify the optimal sled loading conditions for maximizing power production;

4) Compare mechanical variables and optimal loading conditions between recreational and highly trained sprint athletes, and;

5) Determine whether optimal sled loading conditions for maximizing power could be accurately determined from a single unloaded sprint.

Thesis structure

This thesis is presented in a pathway two format (Figure 1). As such, it comprises of a series of chapters, including a narrative review (Chapter 2), and three experimental studies (Chapters 3, 4 and 5) to be submitted to journals for publication. A general discussion and summary chapter (Chapter 6) is provided to give an overview of the studies, how the results may influence practice and future considerations for research.

Chapter 2: A narrative review that specifically focuses on FvP profiling methods in sprinting. This review discusses the development and implementation of these methods for use in profiling sprint running, as well as the implications on determining optimal load for training and future areas of research. It forms the basis for subsequent experiment chapters of the thesis.

Chapter 3: An experimental study that aimed to determine the friction characteristics for an athletic sprinting track, and present a model by which kinetic characteristics can be quantified during resisted sled sprinting. Not only was this chapter necessary for the determination of forces during sprinting for subsequent use in Chapter 4 enabling vertical loading applied to the sled to be calculated in horizontal kinetic friction force, but it offers important critique of the implementation of said devices in the literature.

Chapter 4: An experimental study that integrates the methods outlined in Chapter 3 to determine whether FvP relationships could be accurately determined using multiple trials of sled-resisted sprints. A key outcome from the study was the classification of optimal loading for maximizing power, and a comparison of mechanical capacities between recreational and sprint trained cohorts. A test-retest reliability study was also performed to give insight into the repeatability of the methods.

Chapter 5: A study that builds on the methods developed in Chapter 4, to assess whether the same optimal loading variables could be determined during a single sprint. This chapter uses the same data from Chapter 4, and applies a recently validated method of determining FvP relationships and mechanical variables from an unloaded sprint.
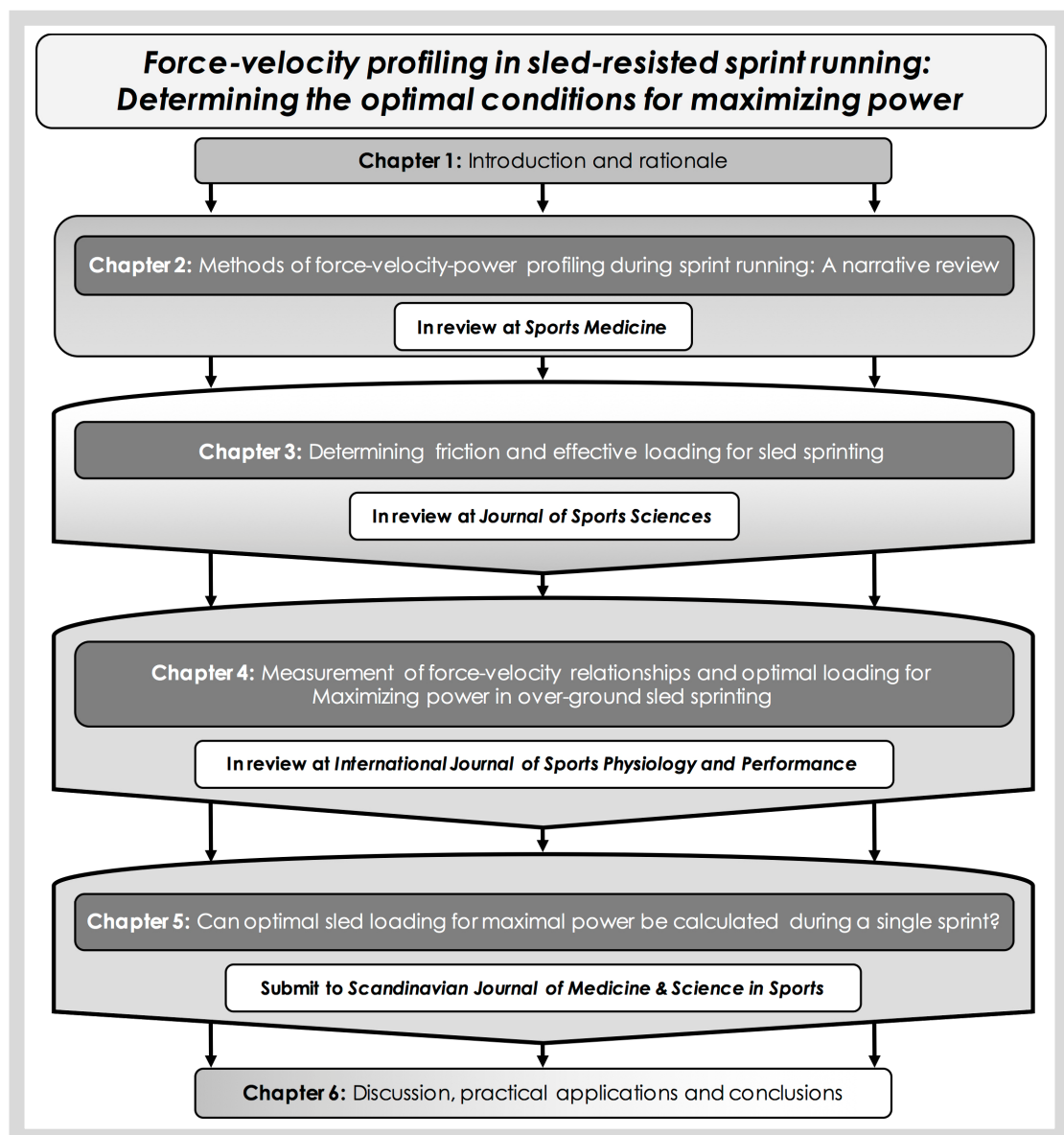
Figure 1. Thesis structure.

Chapter 6: The final chapter summarises the overall findings of the thesis process, including practical applications, limitations, future directions and overall conclusions.

Thesis format

Given the chapters are formatted for publication (i.e. 'pathway 2'), and thus are written to be understood in separation from the thesis body, there are some overlapping and repetitive themes throughout several sections of the chapters. In particular, the introductions of Chapters 4 and 5 (*Measurement of force-velocity relationships and optimal load for maximizing power in over-ground sled sprinting*, and *A simplified method for the assessment of optimal loading for sled resisted sprinting)* present similar information and themes to Chapter 2 (*Methods of force-velocity-power profiling during sprint running: A narrative review*) surrounding the development of FvP profiling techniques and training application of optimal loading. Chapter 4 also implements the methods determined in Chapter 3 (*Determining friction and pulling force during sled sprinting*), and subsequently includes a short summary of the methods used. Moreover, Chapter 5 uses the same operating procedures and data collected in Chapter 4, with additional advanced analyses, and similarly summarises these operating procedures for aiding reader understanding. Chapter 6, while not formatted for individual publication, draws from each chapter for a synthesis of findings for application to the field as a whole. Therefore, given the final chapter features as a summary and practical application of the overall thesis findings, it includes some repetition from the previous chapters.
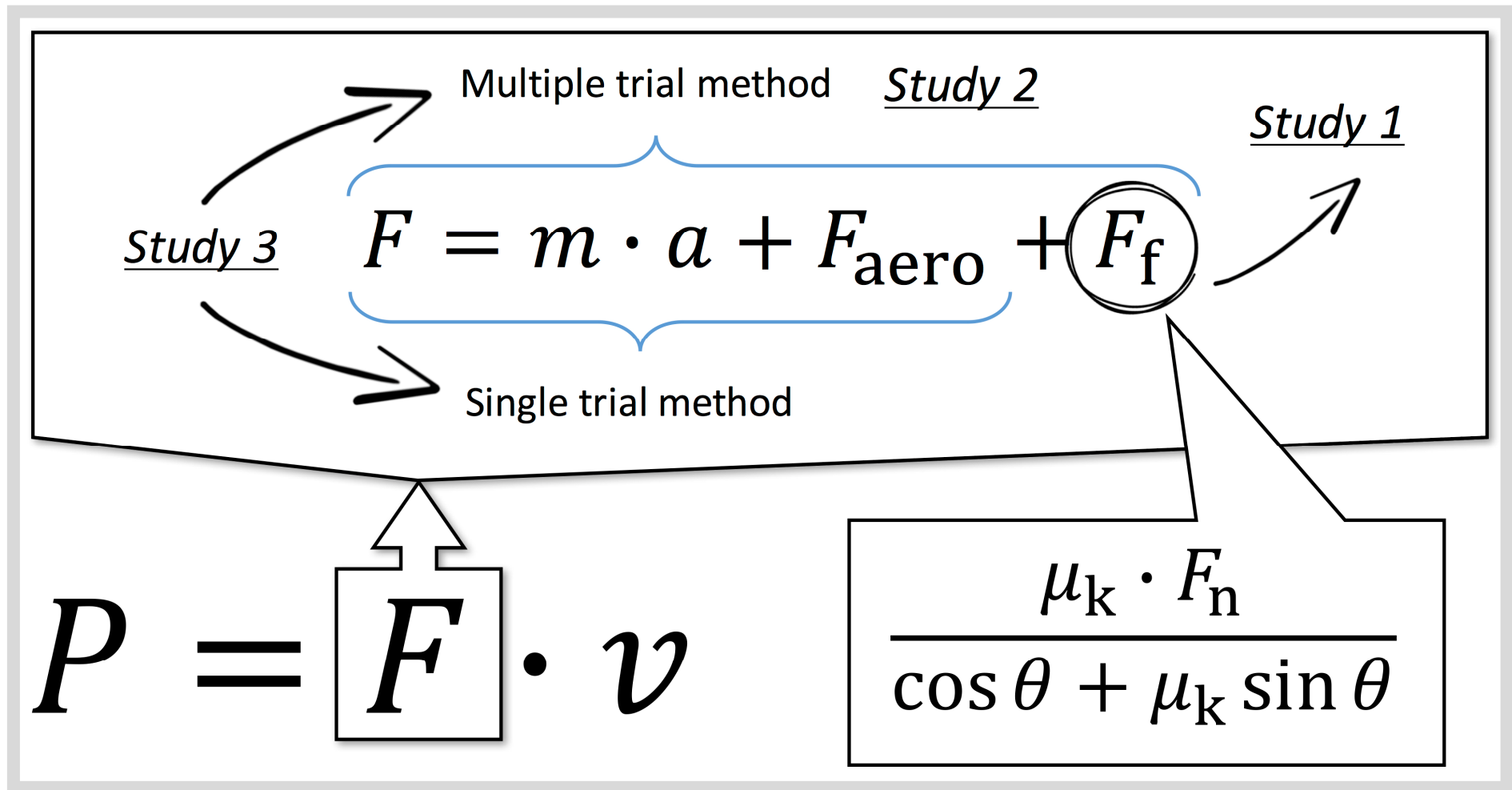
Figure 2. Illustration of thesis and study design with respect to the computation of biomechanical power

CHAPTER 2

METHODS OF FORCE-VELOCITY-POWER PROFILING DURING SPRINT RUNNING: A NARRATIVE REVIEW

Abstract

The ability of the human body to generate maximal power is linked to a host of performance outcomes and sporting success. Force-velocity-power relationships characterize limits of the neuromuscular system to produce power, and their measurement has been a common topic in research for the past century. Unfortunately, the narrative of the available literature is complex, with its development occurring across a variety of movements, methods and technology. This review focuses on the various equipment and methods used to determine mechanical characteristics of maximal exertion human sprinting. Stationary cycle ergometers have been the most common mode of sprint assessment to date, followed by research examining the use of specialized treadmills to profile the mechanical outputs of the limbs during sprint running. The most recent methods use complex multiple-force plate lengths in-ground to create a composite profile of over-ground sprint running kinetics across repeated sprints, and macroscopic inverse dynamic approaches to model mechanical variables during over-ground sprinting from simple time-distance measures during a single sprint. This review will outline these approaches chronologically, with particular emphasis on the computational theory developed and how this has shaped subsequent methodological approaches. Furthermore, training applications are presented, with emphasis on the theory underlying the assessment of optimal loading conditions for power production during resisted sprinting. Future implications for research, based on past and present methodological limitations, are also presented. It is our aim that this review will assist in the understanding of the convoluted literature surrounding mechanical sprint running profiling, and consequently improve the implementation of such methods in future research and practice.

History of force-velocity profiling

The ability of skeletal muscle to generate force and the maximal rate of movement is described in the force-velocity (Fv) relationship. The relationship postulates that for a given constant level of muscular activation, increasing shortening velocity progressively decreases the force produced by the neuromuscular system (Hill, 1938). Mechanical power output (i.e. the rate of performing mechanical work), in this instance, is defined as the product of force and velocity. As the maximal abilities of skeletal muscle to generate both force and velocity are intertwined, the Fv relationship characterizes the ability to produce and maximize power. The term maximal power (P_{max}) describes the peak combination of velocity and force achieved in a given muscular contraction, or movement task (Gollnick & Matoba, 1984; Kraemer & Newton, 2000; Newton & Kraemer, 1994). Fv and power-velocity (Pv) relationships (i.e. FvP) have been examined, *in-vitro* and *in-vivo*, to give insight into the mechanical determinants of performance and further our understanding of movement. There are several modalities through which these characteristics are assessed in movement tasks: 1) Control and manipulation of the force imposed on the movement, and measurement of velocity (isotonic, see Yamauchi & Ishii, 2007); 2) Control and manipulation of movement velocity and the subsequent measurement of force (isokinetic, see Perrine & Edgerton, 1977); 3) Control and manipulation of the external constraints (inertia or weight) and measurement of force and/or velocity (isoinertial, see Murphy, Wilson, & Pryor, 1994). Regardless of the testing conditions, the effort presented is maximal given that the goal is to determine the mechanical limit of the neuromuscular system. Isoinertial experiments are most common as they best represent the natural movement patterns found in sporting contexts, and generally represent a less costly and complex alternative to isokinetic and isotonic modalities. Typically, in an isoinertial experiment external loading conditions are manipulated and the response in the dependent variables of force and/or velocity are measured across single or multiple trials.

The first studies to report concepts of force, velocity and maximal work were based on theoretical methods derived from hydraulicians, where fluid within the muscle has a certain velocity, and any work performed (effort) is proportional to the square of velocity (v); this is described by Euler (see Amar & Le Chatelier, 1914) (see Table 1; Equation 1). The first experimental studies in this area (Hill, 1922; Lupton, 1922) showed that skeletal muscle performed similarly to other mechanical systems where increasing velocity resulted in

Table 1. Historical development of work-velocity and force-velocity relationships

Study and mechanical profiling type	Formula	Equation number
Euler, pre-1820's (as cited in Amar and Le Chatelier, 1914) *Hydraulician theory of muscle fluid (work · v)*	$F = F^{\mathrm{I}}\left(1 - \frac{v}{v^{\mathrm{I}}}\right)^2 \qquad F = F^{\mathrm{I}}\left(1 - \frac{v^2}{v^{\mathrm{I}\,2}}\right)$ with F^{I} and v^{I} representing maximum isometric and velocity of shortening muscle under null loading.	[1]
Hill, 1922; and Lupton, 1922 *Development of work-time to force-time relationship in elbow flexors*	$W = W_0\left(1 - \frac{a}{t}\right) = W_0 - \frac{W_0 a}{t} = LF = LF_0\left(1 - \frac{a}{t}\right)$ where L is amplitude of the elbow flexion occurring.	[2]
Aubert, 1956; and Fenn and Marsh, 1935 *Exponential function derivation from in vitro experimentation*	$F = F_0 e^{(-v/B)} - KV \qquad\qquad F = A e^{(-v/B)} - K$	[3]
Hill, 1938 *Hyperbolic relationship equation (F · v)*	$(F + a) \cdot (V + b) = b \cdot (F_0 + a) = a \cdot (V_0 + b) = \text{constant}$ F_0 is maximum isometric force at null velocity, V_0 relates to the maximal velocity at null force, and a and b are positive constants of force & velocity, respectively.	[4]

decreasing work, and this work-time relationship corresponded to the force-time relationship (Equation 2) (Best & Partridge, 1928). A decade following these studies, an exponential function (Equation 3) was developed from *in vitro* experimentation (Aubert, 1956; Fenn & Marsh, 1935), after which Hill (1938) derived the well-known hyperbolic equation (Equation 4), and has successively been widely used in power based sprint-cycling research (Yoshihuku & Herzog, 1990, 1996). While Hill's rectangular hyperbola accurately fits the kinetic data provided by many single joint actions across differing testing procedures, this relationship does not describe external force production occurring during multi-joint actions (Bobbert, 2012; Jaric, 2015).

While non-linear relationships are typically observed in Fv profiles with individual joints or muscle fibres (Fenn & Marsh, 1935), multi-joint tasks appear to present quasi-linear relationships (for an extensive recent review see Jaric, 2015). While neural mechanism were considered to cause these observations (Yamauchi & Ishii, 2007; Yamauchi, Mishima, Nakayama, & Ishii, 2009), recent evidence suggests segmental dynamics may instead be the main determinant of linear Fv profiles in these tasks; with each joint progressively impeding muscular production of force with increasing velocity, thus decreasing external force (Bobbert, 2012; Bobbert, Casius, & van Soest, 2015). Inverse linear Fv and parabolic power-velocity (Pv) relationships have subsequently been used in recent practice to describe the mechanical capabilities of the neuromuscular system during a range of multi-joint lower-limb movements (for a detailed review of these methods see Soriano et al., 2015): primarily variations on jumping and similar acyclic extensions of the lower limbs (Bosco, Luhtanen, & Komi, 1983; Cuk et al., 2014; Rahmani, Viale, Dalleau, & Lacour, 2001; Samozino et al., 2014; Samozino, Morin, Hintzy, & Belli, 2008, 2010; Samozino et al., 2012; Sheppard, Cormack, Taylor, McGuigan, & Newton, 2008; Yamauchi & Ishii, 2007). Mechanical profiling of acyclic movements typically requires athletes perform multiple trials with increasing external loading in order to incrementally decrease movement velocity (i.e. multiple-trial method). The resultant data is plotted against either load or force (depending on the analysis) to form a linear load-velocity (Lv), or Fv relationship. The difference between the load-velocity and Fv relationships is that normal load (i.e. mass of the resistance provided) is reported in the absence acceleration occurring (e.g. gravity). Given that acyclic movements are generally vertical in nature (e.g. squat jump), the simple Lv relationship roughly

corresponds to the linear Fv relationship. Similarly, during maximal cyclic sprinting, as occurs during sprint-cycling and -running, force-velocity-power (FvP) relationships can be profiled during multiple trials (as above), by using progressively increasing resistance in the form of braking or friction. Furthermore, the same mechanical capacities can be assessed during a single trial by measuring changes in instantaneous force and velocity throughout the foot/pedal strokes of a maximal acceleration phase.

Changes in external force production across varying movement velocities are described by FvP relationships, and are most commonly displayed by the following three variables in literature: the 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); and the P_{max} the system can produce (either during cyclic, or acyclic movements). Principally, these variables characterize the maximal mechanical abilities of the total system (depending on the movement and definition used in each circumstance) pertaining to the generation of mechanical capacities. As the relationship between these macroscopic variables encompasses the entire capability of the neuromuscular system, it is inclusive of mechanical properties of individual muscles (e.g. rate of force development, and internal Fv and length-tension relationships), morphological features (e.g. muscle architecture and tendon characteristics), neural mechanisms underpinning motor-unit drive (e.g. motor unit recruitment, synchronization, firing frequency, and coordination between muscles), and segmental dynamics (Bobbert, 2012; Cormie, McGuigan, & Newton, 2010a, 2010b, 2011a; Yamauchi et al., 2009). F_0 and v_0 represent the y and x intercepts of the linear regression, respectively, and are intrinsically related to the apex of the parabolic Pv relationship, which can be determined via the equation: $P_{max} = (F_0 \cdot v_0)/4$ (see Table 2; Equation/s 8) (Samozino et al., 2012; Vandewalle, Peres, & Monod, 1987). The Fv mechanical profile during explosive lower limb movements can be described by the ratio between F_0 and v_0, or the slope of the linear regression fit for the Fv relationship (S_{Fv}) when force is displayed on the x-axis (see Table 2; Equation/s 8) (Samozino et al., 2012). Additional variables of interest are the combination of force and velocity that elicit P_{max}, often classified in literature as the 'optimal' level for maximal power (F_{opt} and v_{opt}, respectively) (Sargeant et al., 1984). These variables are of particular interest to practitioners as training implemented under a loading scheme representative of F_{opt} and v_{opt} (i.e. L_{opt}) may acutely and longitudinally improve the

Table 2. Development of computation methods for mechanical sprint profiling using multiple and single cycle ergometer methods

Study and mechanical profiling type	Formula	Equation number
Pirnay and Crielaard, 1979 *Least square method of theoretical mechanical variables from multiple sprint method*	$V_{max} = a - bF \qquad V_{max} = V_0\left(1 - \frac{F}{F_0}\right) \qquad F = F_0\left(1 - \frac{V_{max}}{V_0}\right)$ where V_{max} is the peak velocity reached at each braking load (F); V_0 and F_0 equal to the intercepts of the velocity and force axis respectively.	[5]
Peres, Vandewalle, and Monod, 1981 (in Pirnay and Crielaard 1979) *Calculation of peak power from linear force-velocity relationship*	$P_{max} = 0.5F_0 \cdot 0.5V_0 = 0.25F_0 \cdot V_0$ where P_{max} is the peak of the parabolic power-load curve.	[6]
Lakomy, 1985 *Correction of peak-power for inclusion of acceleration*	$F_{corr} = F_{acc} + F \qquad P_{rev} = F_{corr} \cdot V_{rev}$ where F_{acc} is the force required to accelerate the flywheel; P_{rev} and V_{rev} are power & velocity averaged per crank revolution, respectively.	[7]
Vandewalle, Peres, and Monod, 1987 *Determination of peak power from theoretical maximal force and velocity*	$P_{max} = (F_0 \cdot V_0)/4 \qquad S_{Fv} = -F_0/V_0$ where S_{Fv} is the slope of the force velocity graph.	[8]
Seck, Vandewalle, Decrops, and Monod, 1995 *Relationship between velocity and time during a single maximal sprint*	$V = V_0\left(1 - \frac{F}{F_0}\right) \cdot \left[1 - e^{-t/\varphi}\right] \qquad \varphi = \frac{2\pi y v_0 I}{9.81 F_0 r} \qquad V = V_{peak}\left[1 - e^{-t/\varphi}\right]$ where V is pedal rate; T is crank torque corresponding to v; φ is the time constant; y is the gear ratio; r is the flywheel radius, and I is the inertia; F_0 is expressed in kg; and $v_0 = V_0/60$.	[9]
Calculation of mechanical variables from a single maximal sprint	$F_{corr} = F_0\left(1 - \frac{V}{V_0}\right) = F_0 - \left(\frac{F_0}{V_0}\right)v = \left[\frac{F}{F_0} + \left(1 - \frac{F}{F_0}\right)e^{-t/\varphi}\right]F_0$	[10]
	$P = V \cdot F_{corr} = \left[\frac{F}{F_0} + \left(1 - \frac{F}{F_0}\right)e^{-t/\varphi}\right] \cdot \left[\left(1 - \frac{F}{F_0}\right)(1 - e^{-t/\varphi})\right]F_0 \cdot V_0$	[11]

capacity of the system for maximal power production (Kawamori & Haff, 2004).

Mechanical profiling in sprint cycling

Multiple-trial mechanical profiling with cyclic cranks

Mechanical sprinting assessment originated based on a profiling method using a form of Monark cyclic cranks (for extensive reviews regarding cyclic ergometers, see Driss & Vandewalle, 2013; Vandewalle, Driss, & Jin, 2015) redesigned for use with the upper body (Pérès, Vandewalle, & Monod, 1981). The assessment protocol comprised of eight to ten sprints performed against progressively increasing braking forces (F; +1 kg per trial) with consideration of a curvi-linear Pv relationship (Pirnay & Crielaard, 1979). At each load, peak velocity (v_{max}) was measured and plotted against the braking load applied (see Figure 3). Given that at v_{max} the force developed by the limbs is equal to the braking force (assuming zero acceleration), the linear Fv relationship can be plotted under a least-squares regression (see Table 2; Equation/s 5) accounting for braking force and v_{max} alone (Pirnay & Crielaard, 1979). v_0 and F_0 were determined by the intercepts of the velocity and force axis respectively, with P_{max} referring to the optimal combination between velocity and a load of $0.5 \cdot v_0$ and $0.5 \cdot F_0$ (Equation/s 6). These methods were later used to characterize lower body kinetics with the development of a new ergometer (Model: 864, Monark-Crescent AB, Varberg, Sweden) featuring higher load tolerances (Vandewalle, Peres, Heller, & Monod, 1985; Vandewalle, Peres, & Monod, 1987), featuring a reduced volume of trials than these early studies (five to seven trials) due to the Fv relationship's linearity. Similarly, P_{max} of the lower limbs was determined as $0.25 \cdot v_0 \cdot F_0$ (Equation/s 6). It is important to note that the first methods to profile Fv characteristics on cycle ergometry only accounted for the force required to maintain a constant rotation against the flywheel inertia (i.e. F), rather than that required to accelerate it. During the mid-late 1980's researchers (Bassett, 1989; Lakomy, 1985, 1986) proposed a "corrected" approach that considered the force required to accelerate the flywheel (F_{acc}) in addition to F, to determine a corrected force (F_{corr}) (Equation/s 7). Power-output per crank revolution (P_{rev}) was calculated as the combination of velocity per revolution (v_{rev}) and F_{corr}, with its maximum value during acceleration described in corrected peak-power (PP_{corr}).
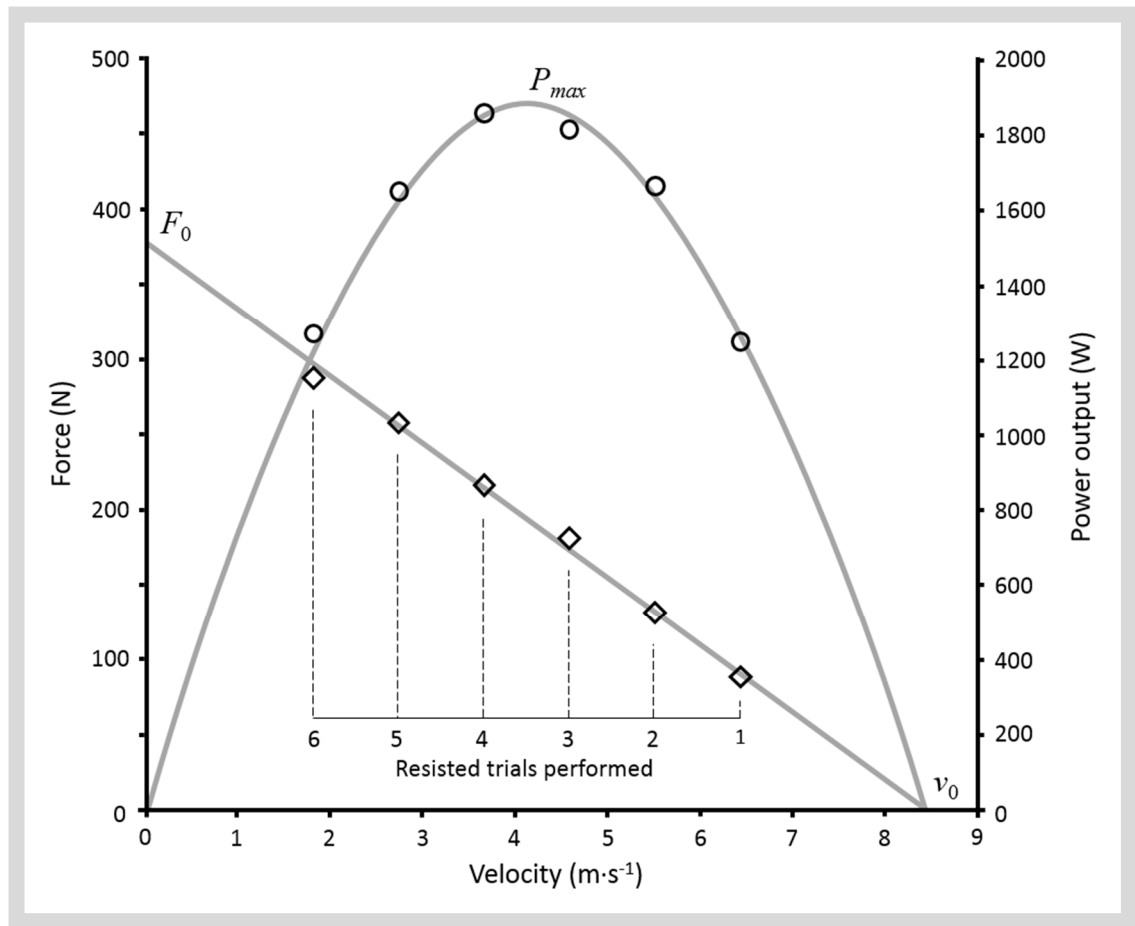
Figure 3. Graphical representation of the relationship between force-velocity and power-velocity as profiled using a multiple sprint method on a treadmill ergometer.
Note that graphically the same relationship can be determined from cycle ergometry, but with torque (N·m) against velocity (rad·s⁻¹). Each data point represents values derived from a single point during an individual trial at different loading or braking 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.

Single-trial profiling method with cycle ergometers

Researchers realized that that once acceleration of the flywheel was accounted for, and with technology featuring a high enough sample rate, it was possible to plot instantaneous decreasing force production (acceleration and friction force) with increasing velocity during a single maximal acceleration bout (Seck et al., 1995). Following calculation of flywheel inertia (see the corrected method above), the relationship between instantaneous angular crank velocity and the torque exerted on the crank (T) were measured during a single maximal cycle sprint. Variables were assessed via a photoelectric cell measuring impulse bursts from the flywheel up to v_{max}, with T calculated as the combination of torque required for

acceleration to overcome the braking load (see Figure 4) (Lakomy, 1986). Importantly, the torque-velocity relationship determined via this single trial method was similarly linear, as compared to the multiple-trial method. When comparing the multiple-trial method to the newly developed single trial method, there was no statistical difference between peak power metrics (i.e. P_{corr} vs. $P_{max}2$ [determined as $0.25\omega_0 T_0$]), and both were expectedly ~10% higher than the uncorrected P_{max} determined from multiple trials. The usefulness of power correction was corroborated by Morin and Belli (2004), who reported underestimation of ~20.4% for power without accounting for the effect of inertia. As methods progressed, variables were averaged over each pedal down-stroke (Arsac et al., 1996; Morin, Hintzy, Belli, & Grappe, 2002; Samozino, Horvais, & Hintzy, 2007), rather than over non-descript periods of time. This was a biomechanically sound progression, given that the data now represented what the lower limbs could develop over one extension - similar to a squat, leg press, sprinting on dynamometric treadmill or force plate system in the ground.
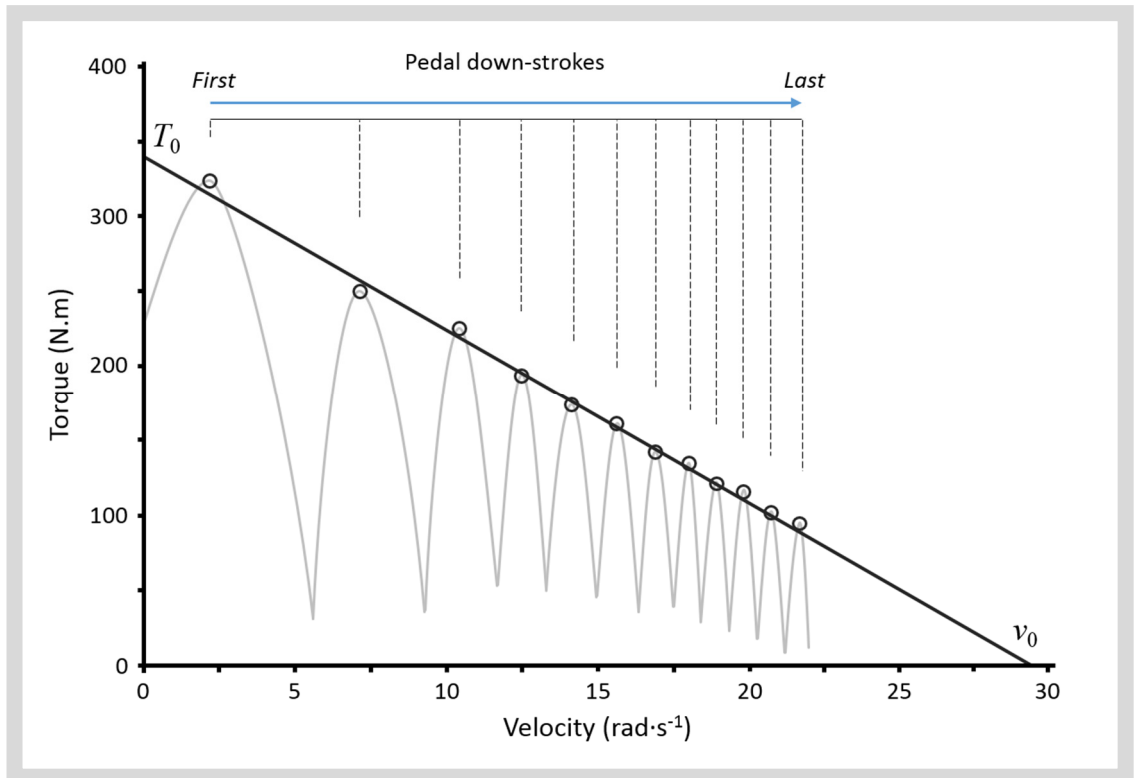
Figure 4. Representation of force- and torque-velocity relationships determined from a single trial. Torque-velocity determined via a single-sprint on a cycle ergometer. The method displayed describes linear regression determined from the peak of each cycle rotation, from the first down-stroke (First), to the last (Last). T_0 and v_0 represent the theoretical maximum of torque and velocity, determined via the y and x intercepts of the linear torque-velocity regression, respectively.

Advancements in technology were responsible these changes, with multiple and single sprint methods reliably (ICC and standard error of estimation [SEE]: v_0<0.88, 2.4%; F_0<0.98, 4.6%; P_{max}<0.98, 3.3%) (Samozino et al., 2007) employed using instrumented cranks or pedals to directly determine torque exerted on the pedals (Dorel et al., 2010). Furthermore, research has implemented similar analyses of power and effectiveness of force application, defined as the magnitude of effective force perpendicular to the crack expressed as a percentage of total force production (Davis & Hull, 1981). These analyses are of note, and their impact will be discussed further with reference to its calculation and importance during sprint running.

Mechanical profiling during treadmill sprint running

For the reason of increasing assessment specificity, researchers have endeavoured to assess the mechanical capabilities commonly determined during cycling, during sprint running. Furusawa, Hill, and Parkinson (1927) performed the first experiments to quantify acceleration of track and field sprinters using a system of wire coils, set at regular known intervals along a testing track, connected to a galvanometer. The subject was equipped with a magnetized harness that recorded a deflection as each coil was passed during the sprint. As the distance (d) between each coil was known (1 – 10 yards), velocity was simply calculated as $v = \Delta d / \Delta t$, and acceleration as $a = \Delta v / \Delta t$, with time measured between each ping from the galvanometer. The first available experimental data concerning Fv relationships during bipedal load-bearing sprinting were derived from an experiment by Best and Partridge (1928), based on the earlier work by Furusawa et al. (1927). This study used the same equipment (which was gifted to the new research group by Hill and colleagues) with the addition of a spectrograph split to increase the accuracy of deflection measurement, and a customized tethered winch system to provide a constant external resistance to the athlete. The experiment effectively confirmed theories of the effects of internal resistance and viscosity of muscle impeding velocity production, and that these could be compared to the inhibiting effects of the external resistance provided in their study. Moreover, the study also noted the similarity of the results to work on air resistance (Furusawa et al., 1927), highlighting that the equations for estimating velocity decrement were accurate, with the exception of the application point of resistance (i.e. around the waist, in comparison to the

whole body).

Modern attempts at experimentally determining mechanical characteristics of the body during load-bearing sprinting occur most frequently using specialized sprint treadmill ergometry. This method requires subjects to propel a treadmill belt while tethered around waist to an immovable stationary point at the rear of the machine. The majority of models calculate power output in a two-dimensional nature, as the interaction of velocity of treadmill belt, measured via rotary encoders in the track motors, and horizontal-force via various loading-cells and goniometers mounted on a non-elastic tether (Lakomy, 1987). These ergometers are either motorized (Chelly & Denis, 2001; Falk et al., 1996; Jaskólska et al., 1998; Morin & Belli, 2004; Morin et al., 2010), with the motor set to apply a resistant torque to compensate for the friction of the treadmill track under the bodyweight of the subject, or non-motorized (Belli & Lacour, 1989; Brughelli, Cronin, & Chaouachi, 2011; Cheetham, Williams, & Lakomy, 1985; Funato, Yanagiya, & Fukunaga, 2001; Lakomy, 1987; Nevill, Boobis, Brooks, & Williams, 1989), with the track simply mounted on low-friction rollers.

Multiple-trial methods using treadmill ergometry

The first author to publish direct measurements of sprint running kinetics was Lakomy (1987), who used an early non-motorized treadmill (Woodway model AB, Germany) to show that power, horizontal force (F_h), and velocity (v_h) could be accurately measured during a 7 s maximal sprint. While the authors did not attempt to profile Fv relationships from the dataset, they did confirm collection of these variables was possible, and therefore paved the way for future investigation. Following studies (Jaskólska et al., 1998, 1999) showed that a multiple-trial method could be used to accurately profile FvP relationships on a sprint-specialized motorized treadmill ergometer (Model: Gymroll 1800, Gymroll, Roche la Molière, France) (see Figure 3 for an example of the multiple sprint method). To provide resistance for each loading condition the track motors were set to apply braking, as a percentage of a predetermined maximum value (i.e. ~1351 N, see Jaskólska et al., 1998, 1999; Jaskólski et al., 1996), to backward movement of the treadmill belt. Resistance was increased across 6 sprints (5% [68 N], 8% [108 N], 10% [135 N], 13% [176 N], 15% [203 N] and 20% [270 N]), during which F_h was estimated via a tether-mounted force-transducer

and goniometer (to correct for attachment angle, and separate vertically oriented forces), and v_h via a sensor system attached to the rear drum of the treadmill belt. Instantaneous power was calculated as the combination of horizontal force and belt velocity. These studies showed that not only were these measurement methods sensitive enough to determine differences between athletes of similar abilities, but the linear profile developed for each subject was independent of v_{max} itself. Moreover, using various methods of variable sampling (instantaneous peak, greatest peak value assessed from 1 s averages, mean power 5 s power), maximal power measures were shown to be reliable (ICC<0.80 to 0.89). When comparing FvP relationships calculated from multiple sprints on cycle and treadmill ergometry, Jaskólska et al. (1999) found measures of power were similar between assessment modalities (r<0.71 to 0.86; P<0.01), albeit with lower readings on the treadmill attributed to the load-bearing nature of treadmill sprinting reducing maximal power output of the lower limbs. Furthermore, the study showed that athletes with a range of maximal speed abilities presented a linear Fv relationship when using the multiple-trial method, presenting high scores for individual correlation coefficients (R^2>0.989) and no significant difference with repeated measurement.

Since these original studies, modernized 'two-dimensional' sprint treadmills have been shown to provide reliable and accurate assessment of sprinting kinetics in various population groups (Brughelli et al., 2011; Cross, Brughelli, & Cronin, 2014; Highton, Lamb, Twist, & Nicholas, 2012; McKenna & Riches, 2007; Ross et al., 2009; Sirotic & Coutts, 2008), although none have repeated the multiple trial FvP experiments of (Jaskólska et al., 1998). There are, however, limitations inherent to treadmill based sprinting assessment (Lakomy, 1987). Earlier literature (Belli & Lacour, 1989; Frishberg, 1983; Jaskólska et al., 1998; Kram, Griffin, Donelan, & Chang, 1998; Lakomy, 1987; Morin & Belli, 2004) sampled instantaneous power values over non-descript brackets of time, often exceeding one-second in duration, resulting in the inaccurate measurement of power and underestimation of velocity (among other errors) (Lakomy, 1986, 1987). While this limitation was often imposed by technology, similarly to the development of cycle ergometry, force values should be averaged over distinct time periods relating to muscular events, in the interest of gaining a holistic view of power production specific to step-cycles during sprint acceleration (Martin et al., 1997). Although this error has typically been avoided in recent studies, with high

sampling frequencies allowing averaging across definite time-windows, this needs to be considered when interpreting findings from earlier studies featuring this limitation. Arguably the most prominent limitation of treadmill sprints using force transducers is that the collection of horizontal force is an approximation, and is vulnerable to being affected by vertical ground reaction force (F_V or GRF-z) signals as the tether moves up and down with each step (movement of <4^0; ~7% contribution of vertical force to horizontal readings) (Lakomy, 1987; Morin et al., 2010). While some studies have used goniometers in attempt to account for this occurrence (Chelly & Denis, 2001; Jaskólska et al., 1998, 1999), this is not common practice (Cross et al., 2014). Moreover, although the output of power from this method is a propulsive measure of horizontally directed force and velocity, collection of these variables occur in disparate locations (along the tether and from the track under the subject's feet). Because of this, the measured output does not drop to a null reading between foot-strikes (flight phase) but to approximately ~20% of the peak value in one study (Lakomy, 1987), depending on technique. This is thought to be due either to a component of body mass acting on the tether during flight, some elasticity in the system, or a combination of these factors. Furthermore, significantly lower v_{max} (e.g. 2.87 m.s^{-1}; see Lakomy 1987) and acceleration on these ergometers are noted due to friction of the belts and inertia of the overall rolling components limiting velocity-ability. For example, in non-motorized treadmills the null track torque is set by manufacturer and does not change throughout the movement, meaning that sprinting speeds are approximately 25-30% lower than over-ground speeds from the same subjects (Highton et al., 2012). This is an issue that persists even with modernized instrumented treadmills, with the exception of feedback controlled models (Bowtell, Tan, & Wilson, 2009), and will be discussed in the following section.

Modern instrumented treadmills and the single treadmill-sprint method

Instrumented treadmills featuring the ability to obtain three-dimensional GRF data have been validated during walking, running and maximal sprinting (Belli, Bui, Berger, Geyssant, & Lacour, 2001; Kram et al., 1998; Morin et al., 2010). These rare and costly machines allow collection of antero-posterior and medio-lateral GRF data (in addition to vertical) and velocity at foot-strike from piezo-electric force sensors positioned under the treadmill (Model: KI 9007b; Kistler, Winterthur, Switzerland). Given the rarity and recent development of such ergometers, until very recently few studies have been published using

such a device (Brocherie, Millet, Morin, & Girard, 2016; Girard, Brocherie, Morin, Degache, & Millet, 2015; Girard, Brocherie, Morin, & Millet, 2015a, 2015b; Morin et al., 2012; Morin, Edouard, & Samozino, 2011; Morin et al., 2010; Morin, Samozino, Edouard, & Tomazin, 2011). These machines meet many of the concerns raised by previous authors; during a sprint acceleration GRF is averaged each single foot contact (approximately 0.15 to 0.25 s) corresponding to a single ballistic event of one push (Martin et al., 1997; Williams, Barnes, & Signorile, 1988) at a high sampling rate (1000 Hz) (Lakomy, 1987; Martin et al., 1997), and horizontal net power output is calculated instantaneously as the product of horizontal force and velocity ($P_h = F_h \cdot v_h$) collected at the same location (i.e. treadmill belt) (see Figure 5).

It was with this new instrumented sprint-treadmill technology (Model: ADAL3D-WR; Medical Development, HEF Tecmachine, Andrézieux-Bouthéon, France) that Morin et al. (2010) showed the ability to determine sprint mechanics during a single sprint. In this method, F_h and v_h are averaged and plotted throughout the course of a sprint for each stance phase similarly to each downward stroke on pedals in early sprint-cycling studies. The steps from maximal F_h ($F_{h_{max}}$) through to that producing $v_{h_{max}}$ are subsequently used to plot the linear Fv relationship (Samozino et al., 2016). The entire Fv relationship is described by the maximal theoretical horizontal force that the lower limbs could produce over one contact at a null velocity (F_{h_0} displayed in N·kg^{-1}), and the theoretical maximum velocity that could be produced during a contact phase in the absence of mechanical constraints (v_{h_0} displayed in m·s^{-1}). A higher v_{h_0} value represents a greater ability to develop horizontal force at high velocities. The criterion of averaging force over a single contact time is important from a biomechanical perspective, as the Fv relationship directly relates to lower limb mechanical capabilities. Values of horizontal maximum power ($P_{h_{max}}$) obtained via this method (when converted to similar time-periods) and mechanical variables (F_{h_0} and v_{h_0}) are congruent with results from comparable subject pools and loading parameters in earlier studies (Cheetham et al., 1985; Funato et al., 2001; Jaskólska et al., 1999; Morin & Belli, 2004), and are highly reliable for test-retest measurement (r=0.94; P<0.01; ICC<0.90).

In addition to the aforementioned FvP relationships, modernized treadmill ergometry allows mechanical effectiveness to be quantified throughout a sprint acceleration phase. Similarly to
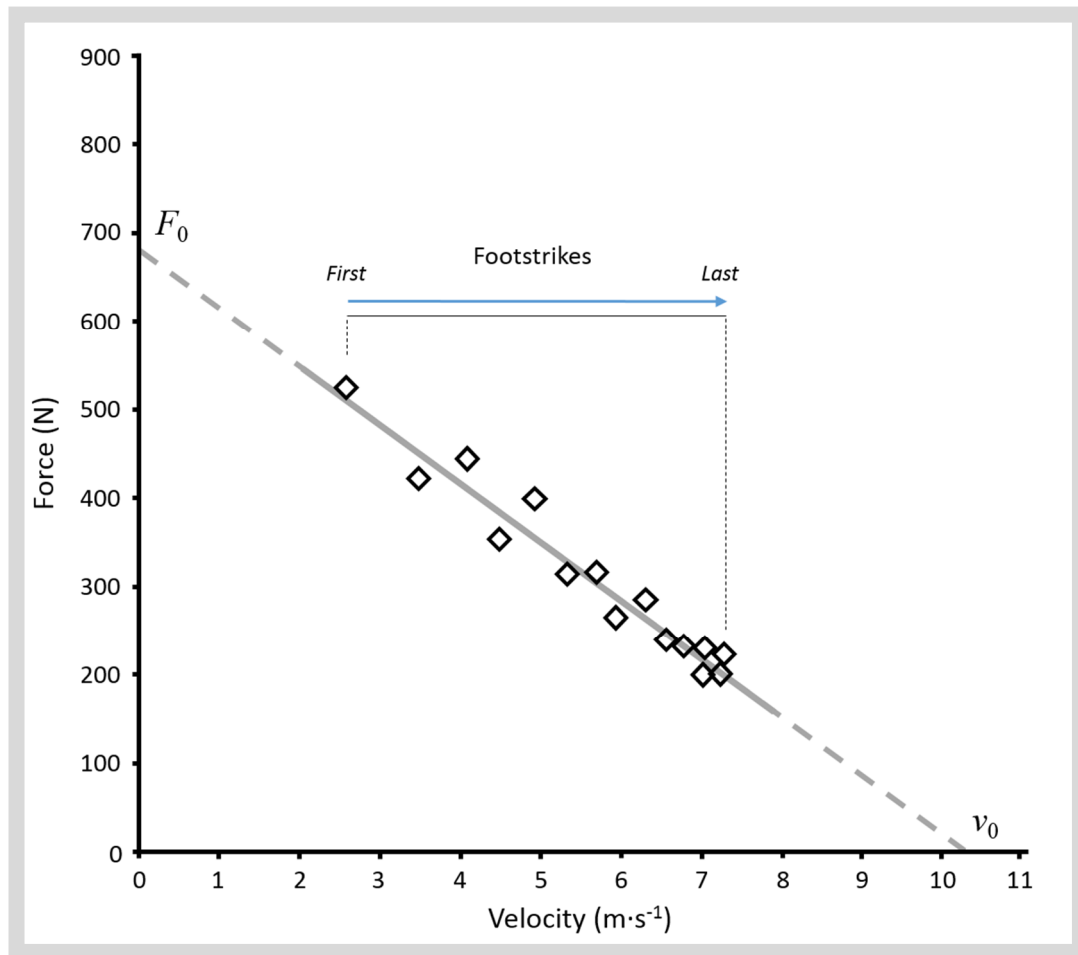
Figure 5. Graphical representation of force-velocity relationship determined from a single sprint on treadmill ergometry.

The data points represent values averaged across each foot-strike, from the first (First) to the last (Last) at peak velocity. Similarly to Figure 3, F_0 and v_0 represent the y and x intercepts, and the theoretical maximum of force and velocity able to be produced in absence of their opposing unit.

cycling literature (Davis & Hull, 1981; Dorel et al., 2010) where indexes of force application can be computed for each pedal down stroke, GRF output from modern treadmills can be expressed as a ratio of 'effective' horizontal portion of GRF data (i.e.) to the total resultant force averaged across each contact phase (i.e. 'ratio of forces'; RF = F_h/F_{tot}) (see Morin, Edouard, et al., 2011). While it is possible (and encouraged) to perform with a technique utilizing maximal RF (i.e. 100%) in cycling, the requirement of a vertical component in sprint running means that it is impossible to present a maximal RF value without falling. Instead, when measured on a sprint treadmill (from a crouched start) sub-maximal values of RF are observed at the beginning of the sprint (28.9-42.4%), which decrease linearly with increasing velocity (R^2=0.707-0.975; P<0.05) (Morin, Edouard, et al., 2011). Furthermore, the slope of this linear decrease in RF with velocity is described as an index of force

application technique ('decrement in ratio of forces'=D_{RF}), and has been shown to be highly correlated with maximal speed, mean speed, and distance at 4 s in 100 m over-ground sprinting performance (r<0.735-0.779; P<0.01) (Morin, Edouard, et al., 2011). Practically, these variables demonstrate the ability to maintain effective orientation of global force production throughout a sprint (independently from the magnitude of the resultant GRF output) under increasing velocity, and provide another level of analysis to profiling simple FvP relationships during sprint running acceleration.

An issue that persists even with the most updated instrumented treadmills is that the application of compensatory friction to the belt appears to restrict the subject's ability to obtain levels of $v_{h_{max}}$ near to over-ground sprint running (Morin et al., 2010; Morin & Seve, 2011). Moreover, the assessment of individualized torque parameters is heavily time consuming, and familiarization persists as a limitation with even the most modern machines (>10 trials) (Morin et al., 2010). Although the reduction in sprinting velocity with torque compensated treadmills varies in significance between studies when compared to over-ground sprinting (e.g. ~20% v_{max}; P<0.001) (Morin & Seve, 2011), one could argue the ability to measure direct kinetics over a virtually unlimited time-period (e.g. change in mechanics with fatigue, across 100-400 m distances; see Girard, Brocherie, Tomazin, Farooq, & Morin, 2016; Tomazin, Morin, Strojnik, Podpecan, & Millet, 2012) potentially outweighs these limitations.

Instrumented sprint treadmills appear to be a reliable and valid means of assessing the mechanical characteristics and relationships of the lower-limbs during maximal sprint running. Although a range of methods and technologies have been used in experimental studies, there remains limited literature regarding the calculation of FvP relationships from such apparatus. Further studies should examine the ability to determine these relationships on more commercially available treadmill ergometers via multiple and single sprint methods. However, the invasive and costly assessment on these machines, including kinematic disparities to practical performance measures, recent studies have sought to quantify these relationships during over-ground sprinting performance.

Mechanical profiling in over-ground sprint running

Until recently, the assessment of sprint running kinetics was only possible via specialized treadmill ergometers discussed earlier in this review. While these methods have been markedly improved since their conception (e.g. Morin et al., 2010), the technology remains rare, assessment is costly and it requires athletes to travel to a clinical setting. Moreover, while a 'specific' mode of assessment, treadmill sprinting remains a dissimilar modality of assessment compared to over-ground sprint running performance (Highton et al., 2012; Morin & Seve, 2011). This may, in part, explain the popularity of simple field methods of lower-body mechanical profiling (i.e. jumping) and why they are widely implemented over the valuable and task specific sprint-profiling methods.

Over-ground mechanical sprint profiling is somewhat difficult due to its non-stationary nature, unlike ergometer based assessment, with requirements for such an approach being the collection of high-frequency data over an acceleration phase until $v_{h_{max}}$ (approximately ~20 to 40 m in team-sport athletes, ~50 to 70 m in pure-speed athletes) (Brüggemann, Koszewski, & Müller, 1999). Despite this, literature has seen kinetics directly quantified during over-ground sprinting, either as single steps within an entire sprint bout (Bezodis, Kerwin, & Salo, 2008; Hunter, Marshall, & McNair, 2005; Kawamori, Nosaka, & Newton, 2013; Komi, 1983; Kugler & Janshen, 2010; Mero, 1988; Mero & Komi, 1986), or instrumented load cell technology used to determine resistive force against a weighted chariot (Martinez-Valencia et al., 2015). Recent studies (Rabita et al., 2015; Samozino et al., 2016) have proven that FvP relationships can be directly assessed during over-ground sprinting, using the methods discussed earlier in this review. Unlike the techniques developed on cycle and treadmill ergometry, there has been no attempt to use traditional multiple trial methods, with researchers instead opting to develop FvP relationships for an unloaded (i.e. free-unresisted) sprint. While there are works currently being developed (in review) using a full length (~40 m) force plate system to fully measure sprinting kinetics throughout a single sprint, the current research uses either multiple unresisted sprint attempts over force platforms transposed together for a single linear Fv relationship (Morin et al., 2015; Rabita et al., 2015; Samozino et al., 2016), or a simple method of determining sprinting kinetics from a single sprint (Samozino et al., 2016).

Composite trial force plate method

Several ground-breaking studies (Clark & Weyand, 2015) were recently published using a method of constructing a single composite mechanical profile from multiple sprints performed over a force platform system (Morin et al., 2015; Rabita et al., 2015; Samozino et al., 2016). This approach, first proposed by Cavagna, Komarek, and Mazzoleni (1971), generates an entire mechanical Fv relationship from seven maximal sprints performed at different starting distances behind a 6.6 m force-plate system of six force platforms connected in series (see Figure from Rabita et al., 2015). The athletes (elite [*N*=4] and sub-elite [*N*=5] sprinters) performed 10-40 m sprints, which enabled the collection of a total of 18 foot-contacts (including those from blocks), at 3-5 contacts per trial for greater or lesser distances, respectively. After the contact-averaged force data were filtered, forward acceleration of centre of mass was calculated, and then expressed over time to determine instantaneous velocity. Data were compiled to determine Fv and Pv relationships, both of which were well described by linear (mean R^2>0.892) and second order polynomial regressions (mean R^2>0.732), respectively (similarly to those shown on earlier cycle and treadmill studies). Furthermore, technical variables were determined for each contact phase, and correlated with overall 40 m performances. Notably, RF averaged across the sprint performance was shown to be the second largest differentiating factor between elite and sub-elite sprinters (9.7%; effect size [ES]=2.31) and the greatest correlation with overall 40 m performance (r<0.933; P<0.01). Peak values were much higher than those reported by (Morin, Edouard, et al., 2011) on an instrumented treadmill (theoretical maximum RF=70.6±5.4%), likely a result of athlete starting from sprint blocks as opposed to from a standing crouched start. Although basic mechanical variables were shown to be related to performance in varying degrees (e.g. v_0=r=0.803; P<0.01, and P_{max}; r=0.932; P<0.001), these results further illustrate the value in further analysis of force orientation characteristics underpinning the horizontal Fv relationship in sprint profiling. Overall, while the model showed that there were no perceivable differences between sprints for the effort involved by the sprinters (ICC<0.686-0.958; CV=1.84-3.76%, for a range of variables), suggesting the effects of fatigue were likely negligible for similar highly trained sprint athletes, the repeated nature and complexity of reproducing such measures limit it's applicability in an applied setting.

Macroscopic approach to mechanical profiling during over-ground sprinting

In conjunction with the methods developed by Rabita et al. (2015), Samozino et al. (2016) developed a method for profiling the mechanical capabilities of the neuromuscular system using a macroscopic inverse dynamics approach (Helene & Yamashita, 2010), applied to the movement of centre of mass during a single sprinting acceleration. Based on the measurement of simple running distance or velocity and time data, gathered either by a set of photo-voltaic cells (as in the case with the primary analysis of Samozino et al. (2016)), high sample rate sports-radar devices (Cross et al., 2015; Mendiguchia et al., 2016; Mendiguchia et al., 2014; Samozino et al., 2016), sports lasers (Buchheit et al., 2014), or GPS units (Nagahara et al., 2016) the method represents a simple alternative to many of the techniques discussed in this review. Such an approach makes several assumptions: 1) the entire body is represented in displacement of COM; 2) when averaged across the acceleration phase no vertical acceleration occurs throughout a sprint (see limitations of the treadmill sprint method above; (e.g. Lakomy, 1987)), and; 3) the coefficient of air drag remains constant (e.g. changes in wind strength). While not an inherent limitation due to its ease of implementation, variables are modelled over time without consideration for changes between and within steps, inclusive of both support and flight phases, rendering assessment and comparison of individual limb kinetics impossible.

In this method, a mono-exponential function (di Prampero et al., 2005; Furusawa et al., 1927; Volkov & Lapin, 1979) is applied to the raw velocity-time data (Table 3; Equation 12) (Arsac & Locatelli, 2002). Following which, the fundamental principles of dynamics in the horizontal direction enable the net horizontal antero-posterior GRF to be modelled for the COM over time, considering the mass (m) of the athlete performing the sprint in association with the acceleration of COM, and the constant aerodynamic friction of the body in motion (F_{aero}) (Equation/s 13 and 14). F_h and v_h values are then plotted to determine Fv relationships and mechanical variables (F_{h_0} and v_{h_0}). As per previous methods, $P_{h_{max}}$ can be calculated as the interaction between F_{h_0} and v_{h_0} (Equations 8) (Samozino et al., 2016; Samozino et al., 2012; Vandewalle, Peres, Heller, et al., 1987), and by the peak of the 2nd order polynomial fit between P_h and v_h. Furthermore, technical variables (RF and D_{RF}) can be calculated similarly to previous methods (Morin, Edouard, et al., 2011; Rabita et al., 2015; Samozino et al., 2016), with the resultant force (F_{res}) in this case being the sum of estimated

net vertical (see Equation 15) and horizontally oriented GRFs. Where previous studies calculated technical variables from the second step, given that individual step characteristics cannot be quantified in this method, from 0.3 s.

Importantly, Samozino et al. (2016) highlighted that the macroscopic inverse dynamic approach was very similar to the multiple force plate method for GRF modelled and computed over each step (F_h, F_{res}, vertical force [i.e. F_v]; r=0.826-0.978; P<0.001). Furthermore, low absolute bias was observed between methods for physical (1.88-8.04%) and technical variables (6.04-7.93%). Data were extremely well fitted with linear and polynomial regressions (mean R^2=0.997-0.999), with all variables presented as reliable (CV & SEM <5%) (Samozino et al., 2016). These results serve to illustrate the strength of such an approach - that estimation of over-ground sprinting kinetics via this simple field method is practically identical to direct measurement via a complex force-plate setup. Furthermore, the method has been shown to be sensitive enough to highlight differences in mechanical variables between athletes with similar abilities, determine between playing positions and track return from injury of rugby and soccer athletes in the field (Cross et al., 2015; Mendiguchia et al., 2016; Mendiguchia et al., 2014). Given the only data required is velocity-time measured with sufficient sampling rate, any practitioner with a reasonable set of photovoltaic timing gates (i.e. >4 sections) or a sports radar could potentially use such a profiling method during their training and assessment batteries. Furthermore, improving technology associated with global positioning systems (Nagahara et al., 2016) and simple cellular devices (MySprint application; article in review) may enable accurate computation of these data in the future.

While the ability to quantify these external variables is valuable due to its simplicity, limitations persist in its inability to quantify individual limb kinetics. If direct assessment of GRF data is required, treadmill methods, or a combination of force platforms and macroscopic approaches are recommended. However, the primary value of this technique is its ability to accurately profile over-ground sprinting mechanics, via a simple and non-invasive on-field testing procedure. Therefore, this profiling method could be performed as part of regular training or testing in many team situations (Morin & Samozino, 2016), illustrating its value for monitoring on-field sprint mechanics longitudinally.

Table 3. Development of computational methods for over-ground sprint running

Study and mechanical profiling type	Formula	Equation number
Arsac and Locatelli, 2002 *Exponential function of COM velocity-time relationship in sprinting*	$v_h(t) = v_{h_{max}} \cdot (1 - e^{-t/\tau})$ where $v_{h_{max}}$ represents the maximal horizontal velocity reached during over-ground locomotion in m.s^{-1} and τ the acceleration time constant in seconds.	[12]
Samozino, Morin, Dorel, Slawinski, Peyrot, Saez de Villarreal and Rabita, 2015 *Acceleration & horizontal orientation of COM travel conveyed as a derivation of velocity over time*	$x_h(t) = \int v_h(t)dt = \int v_{h_{max}} \cdot (1 - e^{(-t/\tau)})dt$ $x_h(t) = v_{h_{max}} \cdot (t + \tau \cdot e^{-t/\tau}) - v_{h_{max}} \cdot \tau$ $a_h(t) = \frac{dv_h(t)}{dt} = \frac{v_{h_{max}} \cdot (1-e^{-t/\tau})}{dt} = \left(\frac{v_{h_{max}}}{\tau}\right) e^{\left(-\frac{t}{\tau}\right)}$ with x as horizontal orientation of COM & a as acceleration of COM.	[13]
Arsac and Locatelli, 2001 *External horizontal net force modelled over time with consideration for air friction*	$F_h(t) = ma_h(t) + F_{aero}(t)$ with m as body-mass; and F_{aero} as the aerodynamic friction force.	[14]
di Prampero, Botter and Osgnach, 2015 *Net vertical ground reaction force modelled over time*	$F_V(t) = m \cdot g$ with g as the gravitational acceleration (-9.81 m.s^{-2}).	[15]

Optimal loading, training considerations and future research

Mechanical profiling allows the computation of the exact conditions underlying maximal power to be determined. These parameters, regularly termed 'optimal', represent a combination of force and velocity values (i.e. F_{opt} and v_{opt}), at which a peak metric of power is maximized (see Figure 3) (Sargeant et al., 1984). Of note, training in these conditions has been suggested as an effective method of increasing the capacity for power production (Kawamori & Haff, 2004; Soriano et al., 2015), which may improve practical performance measures provided the subject displays a favourable profile of Fv capacities (Samozino et al.). Practically, in order for these data to prove valuable they require translation into an easy to set normal load (L_{opt}), either as bandwidth or individual value of external stimulus, that stimulates the mechanical conditions necessary to maximize power production during training.

Typically, literature has shown that FvP and optimal loading characteristics are specific to movement type (Cormie et al., 2007; Kawamori & Haff, 2004; Samozino et al., 2012; Suzovic, Markovic, Pasic, & Jaric, 2013), with a recent meta-analyses (Soriano et al., 2015) describing bandwidths of 0-30% of one-repetition-maximum (1RM) for jump squat movements, 30-70% 1RM for squat movements, and >70% of 1RM for the power clean movement. While increases in mechanical capacity are likely dependent on a number of factors, literature supports the value of training at levels around L_{opt}, F_{opt}, and/or v_{opt} (Wilson et al., 1993) in a movement transferrable to performance. Furthermore, in limited examples the application of optimal force can directly influence performance in competition scenarios (Dorel et al., 2010). Specifically, optimal loading conditions as assessed in sprint cycling (e.g. Linossier, Dormois, Fouquet, Geyssant, & Denis, 1996), in near competition specific conditions, can be replicated by manipulating crank length and gear ratios to enable the athlete to perform a cycle race in practically optimal conditions for power production (Dorel et al., 2005). There is evidence to suggest performing and training closer to F_{opt} may be beneficial for a host of acute performance properties in cycling, including increased mechanical effectiveness (Dorel, Bourdin, Van Praagh, Lacour, & Hautier, 2003; Sargeant, Hoinville, & Young, 1981), decreased movement energy cost (Dorel et al., 2003; Francescato, Girardis, & di Prampero, 1995; McDaniel, Durstine, Hand, & Martin, 2002),

reduced negative muscle actions (Neptune & Herzog, 1999), increased metabolic ratio (Dorel et al., 2003; Morel et al., 2015), and increased resistance to fatigue (Beelen & Sargeant, 1991; McCartney, Heigenhauser, & Jones, 1983). These factors strengthen the rationale for profiling these characteristics where the mechanical constraints during competition can be altered to replicate optimal levels.

Unfortunately, reviews of optimal loading (Kawamori & Haff, 2004; Soriano et al., 2015) have largely focused on acyclic 'single extension' movements using free-weights or smith machines. Furthermore, research examining these themes in cyclic movements has almost exclusively focused on cycling, with differing methods, equipment, varying athlete training backgrounds and performance levels rendering comparison between studies difficult (Jaafar et al., 2014; Vargas, Robergs, & Klopp, 2015). Of the few studies that examine optimal loading for sprint running on treadmill ergometers, Jaskólski et al. (1996) showed that athletes produced peak power at a variable resistance (i.e. torque applied to the belt) of 137-195 N (10.1-14.5% of maximal inbuilt braking resistance) for a range of power indices, and proposed that the results may be dependent on athlete strength and anthropometric characteristics. A few years following, Jaskólska et al. (1999) reported similar results in a group of students (N=32; optimal loading=176-203 N [13-15% braking force]). However both studies simply reported the protocol that presented the greatest level of power, rather than fitting the data with regression equations (i.e. 2nd or 3rd order polynomial), to determine the exact point on the Fv/Lv relationship at which power was maximized (Arsac et al., 1996; Hautier, Linossier, Belli, Lacour, & Arsac, 1996; Hintzy, Belli, Grappe, & Rouillon, 1999). Highlighting this limitation, in the latter example the authors acknowledge that 34% of the athletes did not reach a measureable peak or decline in their power-capabilities with the heaviest loading protocol, highlighting the results presented likely underrepresented these athlete cases. A more recent study by Andre, Fry, and Lane (2013), suffering from the same limitations found that most athletes in their sample (~73%) produced their peak power between 25 and 35% of BM, based on the unsubstantiated manufacturer pre-set electromagnetic braking resistance for treadmill ergometer (Model: Woodway Force 3.0, Eugene, OR, USA). In contrast, using a modern instrumented treadmill, Morin et al. (2010) showed three increasing levels of braking resistance did not significantly alter P_{max} determined during a single sprint, reminiscent of increased force and decreased velocity

output. It is possible that the three resistances selected constituted those around the peak of the parabolic Pv relationship, and significantly increased or decreased resistance may present different findings. Unfortunately, the results from these studies are difficult to compare, given their respective limitations, and the differing technologies and methods over which the analyses were performed. In any case, while the determination of optimal loading on treadmill ergometry offers an additional value by which to measure athlete ability, its relation to training implementation is limited to the assessment modality itself. That is, the conditions determined in these studies may only be replicated in training with access to specialized treadmill ergometry.

At this stage no literature has reported the methods necessary to profile practical optimal loading conditions during over-ground sprinting. That is, no research has used a multiple trial method with progressive resistance, such as sprinting sleds, braking devices, or cable winches, to profile FvP relationships. While optimal loading conditions for sprint running training modalities over-ground has been discussed (Jaafar et al., 2014; Morin & Samozino, 2016; Petrakos et al., 2016; Wilson et al., 1993), authors have typically limiting resisted sprint loading to that which maximizes external stimulus without significantly altering kinematics of the unloaded sprint movement (e.g. <10% decrease in v_{max}, or <12.6% of BM) (Alcaraz et al., 2009; Lockie et al., 2003; Petrakos et al., 2016). While training in this manner no-doubt achieves the goal of maintaining absolute kinematic similarity to unresisted performance, there is evidence to suggest that these loading protocols are far from the conditions necessary for development of maximal power. Of note, the fact that F_{opt} and v_{opt} occur at approximately half of the maximum velocity attained in an unloaded sprint ($0.5 \cdot F_0$ and $0.5 \cdot v_0$, (Sargeant et al., 1984)) would appear to challenge these guidelines, provided increased P_{max} is the goal. Recent evidence suggests training at heavier loads versus more traditional, lighter loading protocols benefits sprint running performance to a greater degree (i.e. 10 vs. 30% of BM loading onto resistive sled device) (Kawamori & Haff, 2004; Kawamori et al., 2013). To date, while v_{opt} has been reported in elite rugby athletes between 4.31 and 4.61 m.s^{-1} (Cross et al., 2015), no specific optimal loading/training strategy has been determined for over-ground sprinting regarding power development. To the author's knowledge, the effects of sprint training using loading protocols of such magnitude (e.g. 50% velocity decrement), both acute and longitudinal performance outcomes, are yet to be

quantified.

The relationship between Fv properties, as illustrated by the slope of the linear regression fit (S_{Fv}), denotes that P_{max} and S_{Fv} are independent from one another. Evidence suggests performance in both jumping and sprint running is reliant not only on the expression of P_{max}, but also by the absolute level and balance between Fv components (Morin, Edouard, et al., 2011; Samozino et al., 2012). Practically, two athletes exhibiting identical P_{max} values could present markedly different Fv relationships (either as a function of a higher or lower F_0 or v_0) (Morin, Edouard, et al., 2011; Samozino et al., 2012), which may be evident in practical performance measures (Morin & Samozino, 2016). Considering Fv characteristics in single extension movements have recently been determined as individualized (Samozino et al., 2014; Samozino et al., 2012), it would seem exercise and load prescription should occur based on both S_{Fv} and P_{max} qualities (Morin & Samozino, 2016). While training at L_{opt} may be a simple approach to increase P_{max}, targeted programming may see prescription of greater or lesser load (force or velocity dominant stimuli, respectively) depending on the orientation of S_{Fv} and the targeted task (e.g. sprint distance to optimize, or level of resistive force to overcome). Importantly, this is an integrative multi-factorial approach, and targeted training based on S_{Fv} orientation may not be as important to novice athletes, who will likely see increases in performance with basic prescription, as opposed to highly-trained athletes. Furthermore, there is currently little research investigating these theories in practice, none of which exists in the realm of sprint running; hence investigation of this nature is required.

Conclusions

The Fv relationship and maximal power the human body can develop are key in sprinting performance. Mechanical capabilities can be measured by various methods during acceleration sprinting in cycling and sprint running (treadmill and overground) methods. While it is well known that adaptations are specific to the velocity used in training, there is an overall paucity of research using FvP methods on updated equipment and further investigation is required in longitudinal studies. Additionally, research determining optimal levels of Fv variables across varying athlete subsets would appear highly valuable for practitioners aiming to enhance the capacities underlying maximal sprinting performance.

CHAPTER 3

DETERMINING FRICTION AND EFFECTIVE LOADING FOR SLED SPRINTING

Preface

This chapter will focus on the assessment of sled pulling force, drawing heavily from sports engineering and sliding friction theory, as a necessary step in quantifying power in a resisted sled sprint. This study presents a method for assessing friction characteristics, and associated effective loading during sled sprinting, for subsequent application in Chapter 4 of this thesis for determining force-velocity-power characteristics. Furthermore, this chapter will offer critique on the common practices of load application and reporting in the literature, and suggest methods for improving the way in which loading is quantified during sled sprinting.

Abstract

Aims. To determine the changes in the coefficient of friction with mass and velocity, and to provide methods of quantifying effective loading during a sled sprint. Based on the findings of previous research, we hypothesized that the coefficient of friction would remain constant with loading and velocity

Methods. A winch device was used to pull a common sprint sled equipped with a high sample rate load cell across a specialized track surface. The testing was performed under variable sled mass (33.1-99.6 kg) with constant velocities (0.1 and 0.3 m.s^{-1}), and with constant sled mass (55.6 kg) and varying velocity (0.1-6.0 m.s^{-1}). Mean force data were assessed across a ~5 m length of standardized track, and 5 trials were performed for each condition to analyse reliability. A single, injury free subject was recruited to perform sled-loaded sprints to provide a practical example of the methods application.

Results. All variables were determined as reliable (ICC>0.99, CV<4.3%). Normal-force/friction-force and velocity/coefficient of friction relationships were very well fitted with linear (R^2=0.994-0.995) and quadratic regressions (R^2=0.999), respectively (P<0.001).

Discussion. The results suggest that the friction coefficient does not change with sled mass,

but is instead dependent on towing velocity. The linearity of composite friction values determined at two different speeds, and the range in values from the quadratic fit (μ_k=0.35-0.47) suggest friction and effective load should be calculated from instantaneous velocity. Equations are provided for application to a sled sprint, including accounting for pulling angle from changing tether lengths.

Practical applications. The methods used in this study allow for the calculation of sprinting kinetics, which should be of interest to those interested in quantifying power metrics during sled sprinting. Furthermore, as friction directly influences loading experienced by the athlete during a sled sprint, practitioners and researchers should account for and report friction coefficients of testing conditions to increase accuracy of load prescription, and allow comparison of results between studies.

Introduction

Dragging, pulling or sprinting with a loaded sled is widely regarded as an effective modality of providing specific horizontal resistance for subsequent enhancement of sprint-running performance (Petrakos et al., 2016; Rumpf et al., 2015). Consequently, literature has seen sprinting sleds used in both acute and longitudinal studies, implemented across a range of athletes and sporting codes (Petrakos et al., 2016). However, the methods through which loading parameters have been quantified makes interpretation and comparison of results between studies difficult.

A large subset of the literature featuring sprinting sleds has used sled-mass ('normal loading'=L_n; i.e. the tare of the sled and added mass, as either absolute or based on body-mass [%]) as a means of reporting and classifying resistance (for a review, see Petrakos et al., 2016). While reporting additional mass in vertically oriented exercises (e.g. jump squats using a barbell) is acceptable due to the movement and associated resistance occurring in the vertical plane, sled training occurs largely in a horizontal plane and is therefore dependent on the conversion of L_n to a horizontal force vector. This is determined almost solely by the friction characteristics of the sled and sprinting surface. Given that the definition of 'load' is the sum of forces acting on a body, the use of sled mass to class loading during sprint-training is inaccurate and misplaced. This presents a problem for researchers and practitioners wishing to compare or duplicate research results, when variations in surface and sled type potentially present different levels of 'effective loading' on the athlete and do not allow for the calculation of instantaneous sprinting kinetics. Some researchers have used velocity decrements in the place of (or in addition to) reporting sled-mass as a way of circumventing the issues introduced by loading based on L_n. Theoretically, this allows for the application of targeted and uniform training stimuli among athletes, and further comparison between studies using similar operational methods. Velocity decrements are typically calculated based on the effect of the stimulus on maximal velocity, and thus apply to a distinct time point within a sprint. Unfortunately, while reporting velocity decrements represents a much more accurate way of quantifying individual resistance than L_n, it still does not quantify the 'effective loading' (i.e. horizontal resistance experienced by the athlete) being applied to the athlete. That is, because the sled resistance protocol is determined by its effect on velocity, rather than actual loading magnitude, calculations of total work, volume, force and power are not possible.

During sprinting an athlete will generate horizontal force equal to the product of the total mass of the system (i.e. body-mass, additional clothing, weighted vest; m) multiplied by the magnitude of acceleration occurring (a_h), combined with aerodynamic drag (Furusawa et al., 1927) (F_{aero}) to present a final horizontal force value (e.g. $F_h = ma_h + F_{aero}$) (Samozino et al., 2016). These methods are well known, and the same basic iterations have been applied in a range of cyclic sprint profiling in cycling (Lakomy, 1985), treadmill sprinting (Morin et al., 2010), and over-ground sprint running (Cross et al., 2015). These calculations apply both to acceleration and maximal phase sprint running, with acceleration in the latter condition simply assumed to be zero (Vandewalle, Peres, Heller, et al., 1987). During resisted sled sprinting, the athlete is required to produce force against additional resistance, represented in kinetic friction force (F_f). This F_f value is determined as the product of the normal force (F_n) associated with L_n, and the interaction between the sled and testing surface. 'Training load' corresponds to the resistive force (F_f) and the inertia of the sled (L_n or F_n), which is added to m to present total system mass. Unfortunately, F_n and F_f are not necessarily synonymous; where F_n is equal to the load applied vertically to the ground under gravity (total sled weight), and is generally easy to accurately and consistently determine, F_f is dependent on friction and is therefore more complex to calculate. The interaction between the surfaces (i.e. the ratio between F_f and F_n) is represented in the coefficient of friction (μ_k), and determines the magnitude of horizontal or 'effective loading', associated to L_n and F_f, applied to the athlete. Furthermore, since F_f depends on the net vertical force applied by the sled (F_n), F_f can be affected (to a lesser degree) by vertical acceleration, resultant of an increased angle of pull (θ). This could occur as a result of changes in athlete height or changing tether lengths between the athlete and the sled device. This is of note, as literature has reported the use of a variety of surfaces (grass, various turfs, athletics track, linoleum) and tether lengths (3.6-23.1 m) (Petrakos et al., 2016), or in some cases has omitted these information altogether, rendering comparisons between studies difficult.

Only two studies have attempted to assess friction for use in sled sprinting (Andre, Fry, Bradford, & Buhr, 2013; Linthorne & Cooper, 2013). Nevertheless, these studies reported a wide range of μ_k values for commonly used surfaces (0.21 to 0.58); which is troubling, considering the possible variation in effective loading from applying identical L_n parameters on surfaces at either extreme of this range. The results from these studies were conflicting,

with Andre, Fry, Bradford, et al. (2013) noting changing μ_k values with added mass, and the Linthorne and Cooper (2013) noting no changes with either mass or the range of tested velocity. Of note, the experimental velocities were either not reported (Andre, Fry, Bradford, et al., 2013), or were low compared to free sprinting (0.5-2.3 m.s^{-1}) with seemingly incorrect statistical processes (multivariate regression performed on changes in F_f with mass and velocity, rather than μ_k) (Linthorne & Cooper, 2013). Moreover, large ungainly sled designs and limitations in technology (hand driven winching devices and simple strain gauges) possibly limit the application of their findings to practical on-field sled sprinting.

Therefore, the aim of this study was to determine the changes in μ_k values across mass and velocity, and to present an accurate and reliable method by which F_f can be determined using a common training sled, load cell and winch system. A secondary aim was to apply this method and quantify μ_k values for a common training surface, and provide, if required, calibration equations for future sport practitioners or scientists using similar equipment who wish to accurately quantify F_f during sled sprinting.

Methods

Subjects and protocol

This study proposed a simple method for determining μ_k and F_f to be implemented during sled sprinting using a sliding sled design common in engineering research (Persson, 2000). The testing consisted of using a winch device to pull a sprint sled with a range of sled mass, and with constant mass and varying velocities, across a specialized track surface. For each trial, data were analysed once the sled had reached and maintained a constant velocity. This allowed assessment of F_f for each sled-mass or velocity condition, in the absence of force due to acceleration or deceleration, with the aim of μ_k on a common surface used for athletic training (Blau, 2008; Persson, 2000). A single, injury free subject was recruited to perform sled-loaded sprints to provide a practical example of the application of the method. Ethical approval for this section of the study was granted by the Auckland University of Technology Ethics Committee (15/61).

Equipment

The testing was implemented using an immovable motorized winch, comprised of a specialized 9kW motor (Model: CMP100M Servo gear-motor, SEW-Eurodrive, Auckland, NZ), mounted to a cable drum, controlled by a Variable Speed Drive (see Figure 6). The unit featured an estimated effective load tolerance of ~1100 N, and a peak acceleration capability of ~5 $m.s^{-2}$. The unit was set to tow a heavy-duty sprint sled (5.64 kg; Model: HT 50mm Sled, GetStrength, Auckland, NZ) loaded with a selection of calibrated Olympic style powerlifting plates (Model: PL Comp Discs, Eleiko Sport, Halmstad, SWE). The sled was engineered from folded brushed stainless steel, with smooth flat railings contacting the track surface (L×W: 45×30 cm, contact area: 265 cm^2). The sled was attached horizontally to the winch device by a 4 mm wire cable and high-tensile steel karabiners. Throughout each trial, instantaneous force-time data was collected via a load-cell (Model: 250 kN S-Beam Load cell, Meltrons Millennium Mechatronics, Auckland, NZ) attached to the front of the sled, and a 100 Hz 18-bit resolution wireless sender unit (Mode l: Wireless DAQ module [WLS-9163; NI-9219], LabVIEW, National Instruments Corp, Austin, TX, USA) synchronized with a custom designed software program (LabVIEW, Build version: 14.0, National Instruments Corp, Austin, TX, USA). The load cell was calibrated across a wide range of tensile and compressive forces (approximately -1100 to 1100 N), and zeroed in an unloaded state between trials. The Variable Speed Drive provided constant towing velocity to the sled, and subsequent velocity-time data. Testing occurred on a 35 m length of indoor Mondo rubberized athletics track.

Friction experiment procedures

For a given trial, the operator would secure the cable from the winch to the sled at a distance of 35 m. The winch was operated remotely to accelerate and provide a constant towing velocity across variable distances and time, each being dependent on the load applied to the sled and the speed of the trial. A total of 13 testing conditions were used, separated into constant velocities with variable sled mass (*N*=8), and constant sled mass with variable velocity (*N*=5). For variable mass, a range of 4 loading protocols (33.1, 55.6, 77.8, and 99.6 kg) were chosen to be representative of that used in sprint practice and research. Five trials were used for each mass in order to assess reliability at 0.1 and 0.3 $m.s^{-1}$. For variable velocity,
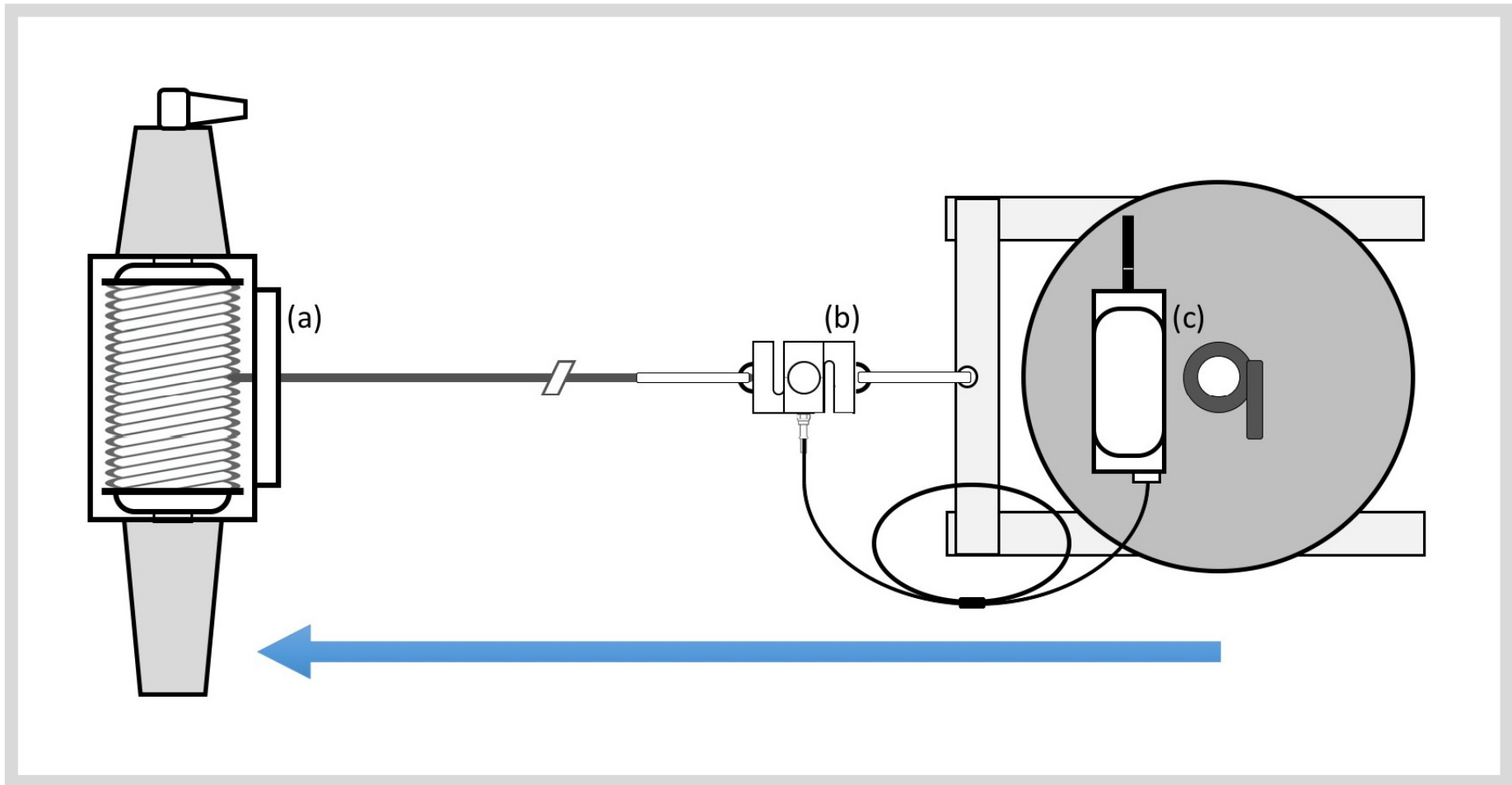
Figure 6. A pictorial representation of the experiment winch and sled setup.
Figure denotes (a) an immovable motorized winch; (b) an s-beam strain gauge attached via high tensile karabiners; and (c) a common sprinting sled, loaded with Olympic style weightlifting plates and mounted with a wireless sender unit. Note that figure is not representative of scale.

a range of five velocity protocols (0.1, 0.3, 2.0, 4.0 and 6.0 m.s^{-1}) and a sled mass of 55.6 kg were selected as a span of loading representative of a typical moderate-heavy sled sprint, and the upper limit of the velocity ability of the winch device (<7 m.s^{-1}), respectively. The lower speeds of 0.1 and 0.3 m.s^{-1} were selected to provide convergent validity to a portable system to be used in future projects of friction measurements on other surfaces. Five trials were used for each velocity in order to assess reliability.

Data analysis methods

Data collected from the custom built software were analysed using a similarly custom built analysis platform (LabVIEW, Build version: 14.0, National Instruments Corp, Austin, TX, USA). The subsequent force-time data were averaged across a 2-5 s period, corresponding to a ~5 m length of track in the centre of the 35 m collection bracket. This allowed for both acceleration (4 m.s^{-2}) and deceleration (-4 m.s^{-2}) of the sled with the high velocity trials. Selection of the data for analysis was corroborated via comparison with a rotary encoder built into the winch, in association with a strip of metal built into the track, which produced a visually perceptible spike in the force-time data (see Figure 7). In all but the fastest trials, the plateau in velocity was very clear in the force trace, and thus all auxiliary processes were only necessary with latter fast trials.

Mean F_f data for each variable-sled-mass protocol were then plotted against F_n to comprise a linear least-squares relationship. This relationship was calculated for the two winch speeds (v_1=0.1 and v_2=0.3 m.s^{-1}), using the following calculation:

$$\mu_k = F_f/F_n \tag{1}$$

where F_f is equal to the horizontal pulling force (N), determined by a constant velocity pull at a given F_n. Note that in the variable velocity experiment, data were fitted with polynomial relationships, which denotes that μ_k is determined based on velocity (equation and rationale presented below). From here, the model proposed to determine F_f was:

$$F_f = (\mu_k \cdot F_n)/(\cos\theta + \mu_k \sin\theta) \tag{2}$$

where μ_k is the coefficient of kinetic friction, and F_n is the total vertical force of the sled in Newtons (the total mass of the sled multiplied by acceleration due to gravity [-9.81 m.s^{-2}, as the normal gravity for Earth]) (Moritz, 1980). μ_k and angle of pull from the sled tether (θ)
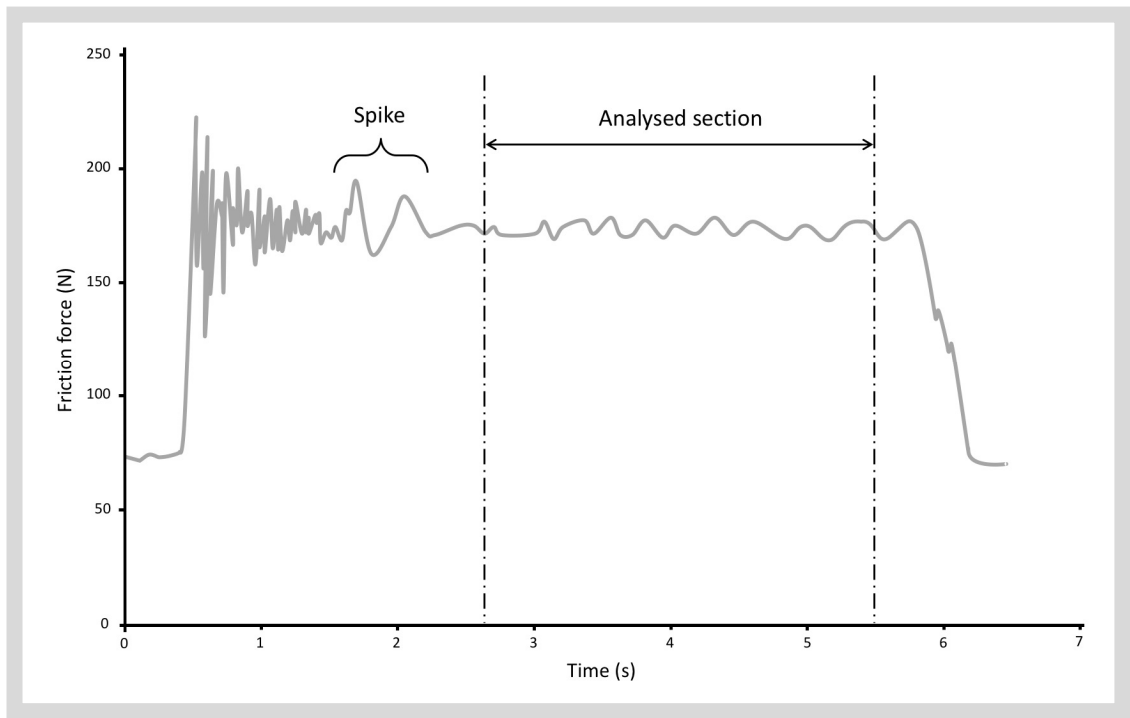
Figure 7. Illustration of raw force-time data and associated selection protocols from a typical trial. Data spike = An inflection in the force-time data caused by metal strip on the track surface, signalling the approximate start of the analysis window; Analysed section = Data plateau corresponding to ~5 m strip of track for analysis.

are estimated using the following equations:

$$\theta = Sin^{-1}(h_t/c) \tag{3}$$

where h_t is the attachment height of the tether to the winch (or athlete), and c is the length of the tether. In the case of the primary experiments of this research, this equation was not used due to a zero θ (i.e. equal height of attachment between the sled and winch).

Applied example

An academy level rugby athlete (N=1, age=26 y, gender=male, weight=98.5 kg, stature=1.98 m) performed 3 sled sprints with a 39.4 kg mass (40% of body-mass), on the Mondo testing surface used for the friction modelling experiments. The athlete was highly familiarized with the testing procedures, and performed a familiarization session <1 week prior to testing. The athlete performed a 15 min warm up, consisting of dynamic stretching and submaximal stride-outs, following which a 30 m sled-resisted maximal sprint was performed from a standing split stance. Instantaneous velocity-time data (46.9 Hz) were collected via a sports radar (Model: Stalker ATS II, Applied Concepts, Dallas, TX, USA) set behind the athlete,

with identical operating procedures to those described in detail in previous research (Cross et al., 2015). The trial with the highest maximum velocity ($v_{h_{max}}$) was selected for analysis.

Statistical analysis methods

Linear regressions were used to describe $F_f - F_n$ relationships, with accuracy of fit reported as R^2 and *P*-value (*a*=0.05). The linear regression was forced to intercept zero, based on well-known sliding friction theory (Blau, 2008). A 2nd order polynomial quadratic regression was used to describe the relationship between μ_k and velocity. The polynomial fit was decided based on the change in R^2 values of multiple equation fits (linear, exponential, and logarithmic). Quadratic regressions were similarly described with R^2 and *P*-values. Descriptive data for each method are provided as means ± SD. Reliability of each method was assessed with the intra-class correlation coefficient (ICC) and coefficient of variation (CV%), calculated across 5 trials.

Results

Results of the analyses are presented in Table 4. When mass was varied with constant velocity, F_f increased linearly with F_n (v_1, R^2=0.996 and *P*<0.001; v_2, R^2=0.994 and *P*<0.001), and the slope of the $F_f - F_n$ relationship (i.e. composite μ_k) was different between the two velocities (μ_k=0.34 and 0.37 for v_1 and v_2, respectively; Figure 8). The $F_f - F_n$ relationship accurately followed a parabolic relationship (R^2>0.999, *P*<0.001; Figure 9), with the peak of the 2nd order polynomial occurring around 5.3 m.s^{-1}. Both methods were presented as reliable (variable mass [v_1 and v_2], ICC=0.96-0.98 and CV=3.8-4.3%; variable velocity, ICC=0.99 and CV=3.0%). The equation determined via the quadratic fit of μ_k with consideration for instantaneous velocity (v_h) is described below:

$$\mu_k = -0.0052 v_h{}^2 + 0.0559 v_h + 0.3184 \qquad [4]$$

Table 4. Descriptive data and reliability of friction experiments

Testing Conditions	Friction force (N)		Reliability
	M	±SD	(CV%; ICC)
Normal force (N) v_1			4.3; 0.98
324	89.2	±3.15	
545	176	±6.30	
763	250	±15.3	
977	329	±16.9	
Normal force (N) v_2			3.8; 0.96
324	108	±0.92	
545	183	±5.31	
763	272	±12.7	
977	372	±16.5	
Velocity (m.s^{-1})			3.0; 0.99
0.1	176	±6.30	
0.3	183	±5.31	
2.0	223	±8.59	
4.0	250	±9.94	
6.0	254	±1.54	

Values are means ±SD; CV% = coefficient of variation; ICC = intraclass correlation coefficient; m = metre; s = second; N = Newton.
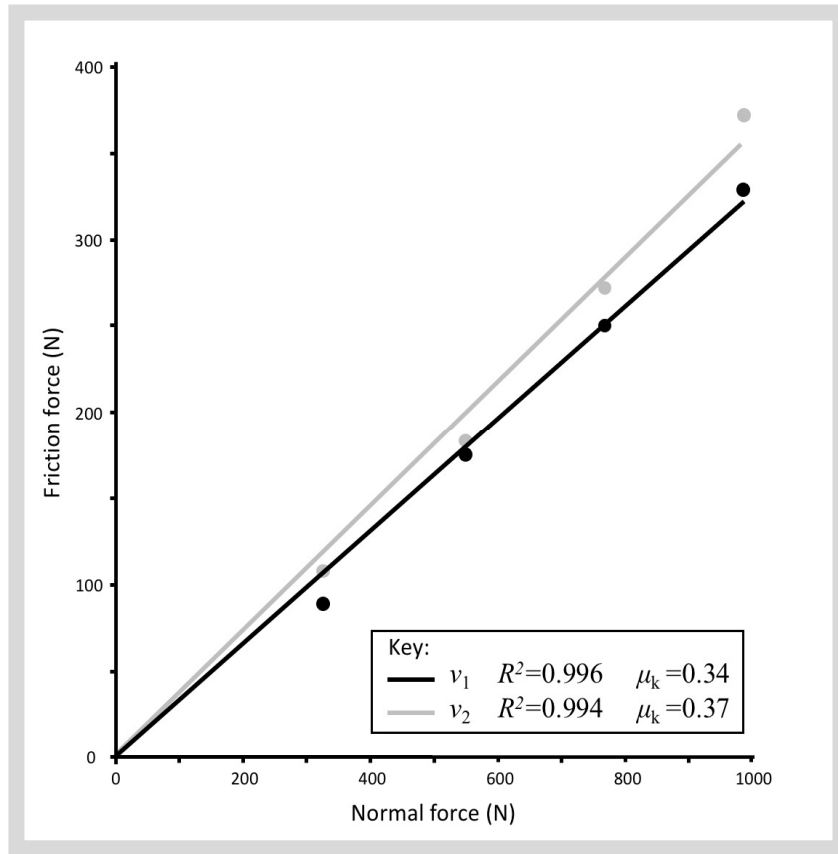
Figure 8. Composite F_f - F_n relationships, determined at two different velocities by varying the load applied to the sled and measuring the pulling force across multiple trials.

Key:

v_1	$R^2=0.996$	$\mu_k=0.34$
v_2	$R^2=0.994$	$\mu_k=0.37$

$$\mu_k = -0.0052v^2 + 0.0559v + 0.3184 \quad R^2=0.999$$
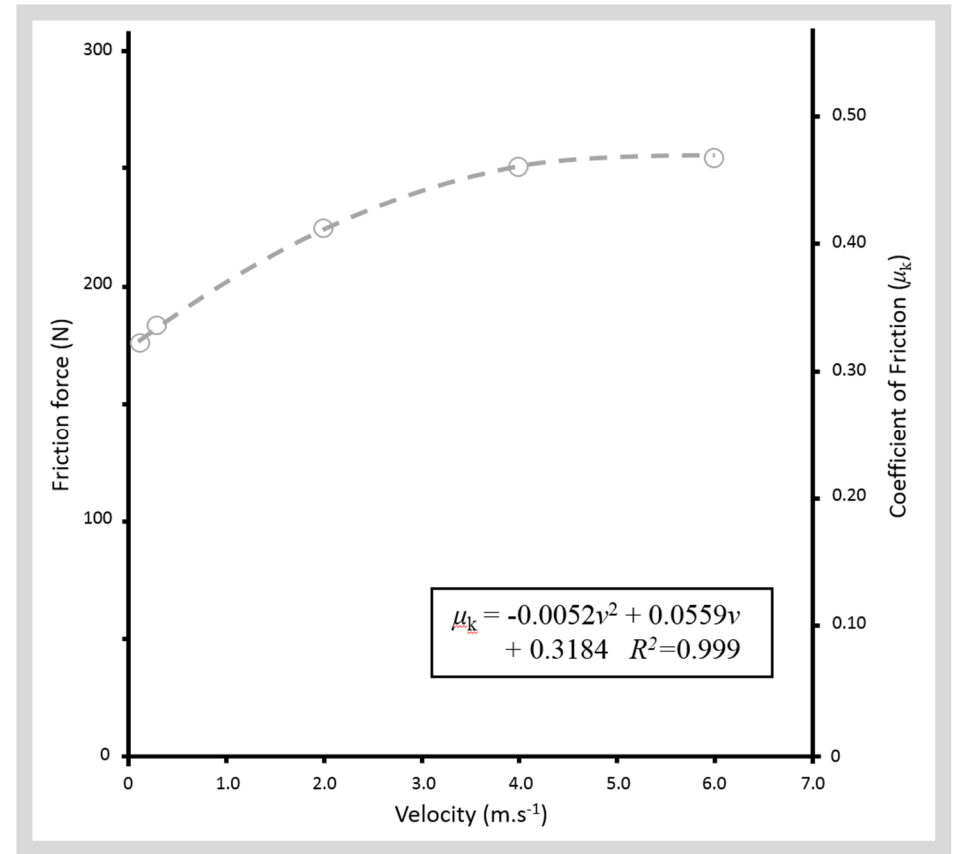
Figure 9. Representation of the change in μ_k with changing velocity, and constant F_n

Discussion

In this study, the interaction between the sled and the athletics track presented two well-predicted relationships. A linear relationship was observed in friction force with the addition of mass, suggesting it did not affect μ_k. It was assumed that manipulation of pulling velocity would not change the observed μ_k, however this was not the case. The $F_f - v$ data followed a parabolic relationship, with μ_k increasing until around 5 m.s^{-1}. The results suggest that towing velocity might be a determining factor of sled resistance for rubberized athletics tracks. Practically, it appears the effective loading on the athlete changes throughout the sprint, and athletes with different velocity abilities will experience different resistance levels at their maximum ability.

The $F_f - F_n$ relationship generated at the two tested velocities (v_1 and v_2) was linear, supporting the hypothesis (and aligning with previous research (Linthorne & Cooper, 2013) that μ_k would remain constant with increasing sled mass. v_1 and v_2 presented different composite μ_k values (0.34 vs. 0.38, respectively), considered to be due to the change in velocity. This was corroborated by the similarly very well fitted parabolic relationship observed with constant mass and increasing velocity. Using the prediction equation supplied by the polynomial fit (Equation 4), modelled μ_k values ranged from 0.34 as the lowest tested value, to 0.47 as the peak of the parabola. This range is congruent with normative sliding friction values of similar materials (Blau, 2008; Persson, 2000), and those published using similar methods (Andre, Fry, Bradford, et al., 2013; Linthorne & Cooper, 2013). While velocity is typically considered independent of μ_k, interaction between these variables is not unusual when examining engineering literature (Braun & Peyrard, 2011). It is possible that deformation of the track surface with speed (i.e. heat, surface compressibility) may have contributed to results, given the relative irregularity of the Mondo track composition (i.e. quilted rubberized piles) when compared to a surface like brushed steel or smooth concrete. In this instance, the changing friction characteristics with increasing velocity could be attributed to the 'stick-slip' mechanism (Persson, 2000). This phenomenon relates to the occurrence of relatively intermittent motion where an object will 'stick' to a surface until the tension force reaches the value of static friction, at which point the sled will 'slip'. Once the

sled has moved a particular unit of distance, and the tension in the system has reduced (i.e. the system spring) it will 'stick', and the process will be repeated. The stick-slip mechanism is known to be largely velocity dependent, increasing μ_k with velocity until a localized maximum is reached, after which μ_k decreases with increasing velocity (Berman, Ducker, & Israelachvili, 1996). This mechanism is typically illustrated with a mass and spring setup (e.g. Blau, 2008), however the concept is universally applicable given that all systems have some degree of imbued elasticity when compressed or pulled. Thus, the assumption is that this same mechanism could plausibly apply in our setup.

We are aware of only two similar studies in the sports science literature (Andre, Fry, Bradford, et al., 2013; Linthorne & Cooper, 2013), neither of whom support our findings of changes in μ_k with increasing velocity. Notably, in the case of Linthorne and Cooper (2013) while using a range of velocities to assess its effect, the fastest condition was low compared to those reached during sled sprinting and the point at which peak μ_k was observed in the current experiment (<2.5 vs. 5.3 m.s^{-1}, respectively). Furthermore, their comparative procedures were unclear, with basic technologies and operating procedures (i.e. hand-held scale and hand-towed sled). While the authors did not assess a Mondo athletics track, the value of μ_k=0.58 for Rekortan track is somewhat comparable with that reported at the higher velocities in our study (μ_k=0.47). However, the exact speed at which this relationship was determined was not clearly reported. While the technology implemented by Andre, Fry, Bradford, et al. (2013) was more advanced, the applicability of their findings was somewhat limited by the use of a very large custom built sled with carpet rails (~50 kg), towed at a low velocity across a linoleum lab floor. Interestingly, Andre, Fry, Bradford, et al. (2013) observed changes in μ_k with increasing mass, perhaps explained by compressibility of the carpet changing the interaction between the surfaces (Persson, 2000). In any case, while the study raised some interesting mechanistic questions, its results were relatively non-transferable to over-ground sprinting.

In order to assess the effect of using either of the modelled methods, we applied the two relationships to the velocity-time data of an athlete sprinting with a L_n of 39.4 kg up until $v_{h_{max}}$. The practical difference between accounting for velocity and using the constant μ_k determined from v_1 presented an average underestimation of 14% in F_f values (peak of 17%,

for 166 vs. 137 N). Note that due to μ_k being calculated on instantaneous velocity, the magnitude of bias between methods changes throughout the various sprint phases (see Figure 10). For example, the athlete reached a $v_{h_{max}}$ of 6.2 m.s^{-1} which resulted in a modelled F_f of between 119 and 166 N (40% increase), for the beginning and peak velocity of sprint (respectively). In any case, the application of these methods depends largely on the point at which any subsequent calculations are occurring. For example, if quantifying kinetics at $v_{h_{max}}$ or throughout the sprint is key, then it may be best to use an equation based on velocity (see Chapter 4). However, if simple tracking of sled mass is the goal across a longitudinal study, or the reporting of acute changes reminiscent of a particular loading protocol, then practitioners or researchers may wish to select an intermediate velocity on which to base their calculations. For example, modelling at 2 m.s^{-1} reduces the average difference in estimation to an overestimation of 4.3%, based on the prediction equation fit with an L_n of 39.4 kg, although the disparity is major in the first instance of the sprint by 40% F_f. Further investigation is required, however, to quantify these relationships on other surfaces and with other sled devices.
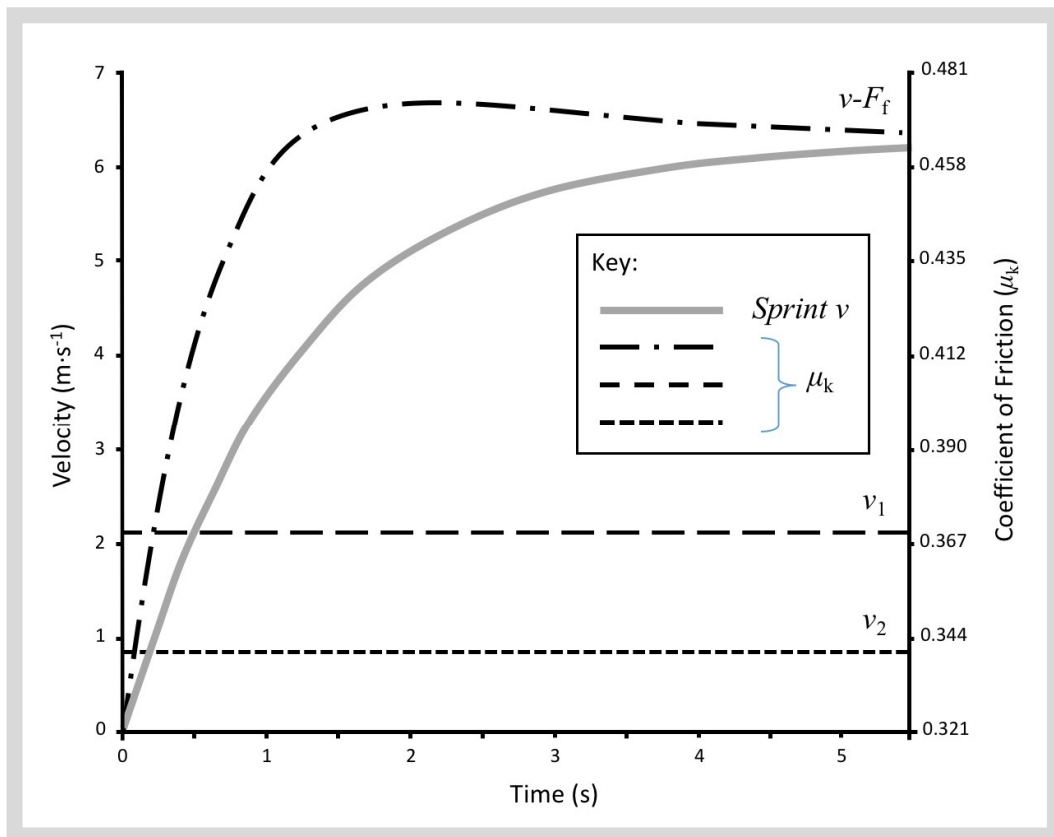
Figure 10. Illustration of the different methods of determining friction force, displayed in reference to the filtered velocity-time data of a 30 m sled-sprint with 22.6 kg L_n.

While the effect of surface on various sporting outcomes has rarely been investigated (Nigg & Yeadon, 1987), there is a large body of evidence providing a basis for these theories in the engineering literature (Blau, 2008). While it is unclear whether these differences will be worthwhile in every case, given our findings there is a potential for large margins of error when ignoring friction factors. For example, while acknowledging their possibly inaccuracy, the values reported by Linthorne and Cooper (2013) (μ_k=0.21 to 0.58) suggest that sled training on disparate surfaces could constitute a large variation in effective loading on the athlete when maintaining a given L_n. As an example, even when using a similar athletics track surface (Mondo vs. Rekortan; current study vs. Linthorne & Cooper, 2013), a 50 kg L_n could represent a difference in effective loading of ~5 kg (determined at $v_{h_{max}}$, ignoring angle of pull calculations). The fact that other surfaces may present a ~15 kg difference when similarly modelled strengthens the need for more thorough load quantifying in both research and practice. Furthermore, tether length could further affect F_f via the inclusion of vertical orientated force. Unfortunately, the measurement of attachment angle is complex in-field, due to changes in trunk lean with acceleration changing the variable throughout the course of a sprint. It should be noted, that differences in angle of pull present substantially less practical effects on kinetics than those reminiscent of μ_k changes (using a μ_k of 0.47, an L_n of 39.4 kg, and an h_t of 1 m; c of 3.3 and 23.1 m = F_f of 190 and 182 N, respectively), and therefore approximations based on standing attachment height are likely acceptable until more practical measurements are validated.

Limitations

While it was assumed that the single sled-mass protocol of 55.6 kg used to comprise the $\mu_k -v$ relationship represented that of the entire $F_f - F_n$ relationship, determined at each velocity, it is possible that the linear trends observed at low velocities may not be representative of greater or lesser mass at higher velocities (CV=4.3%). Unfortunately, these lower velocities were necessary due to the load-tolerances of the winch, and the reduced useable testing area with increased distance (needed for acceleration and deceleration). While the extreme linearity of the $F_f - F_n$ relationship determined at two low velocities would seem to support this assumption, further research is necessary to confirm this. Furthermore, it is recognized that the two composite relationships represent different μ_k values than those determined via

the prediction equation from the $\mu_k - v$ relationship (v_1 and v_2, μ_k values of 0.34 and 0.38 vs. 0.32 and 0.34, respectively). This could be due to several factors, including an increased error measurement with increasing loading (SD of >15 N with heavier sled mass, compared with <3 N with lower protocols). Practitioners and future researchers should consider which relationship better suits their needs.

Practical Applications

Practitioners and researchers should consider sled resistance in units of force, determined by friction, rather than normal loading. Velocity appears to be a determining factor of μ_k on athletics track surfaces, and should therefore be accounted for in order to quantify pulling force throughout a sprint. Future research should look to apply these methods to assess sprinting mechanics throughout an entire sprint, or assess the effective loading and mechanical characteristics of a range of sled-sprint protocols.

CHAPTER 4

MEASUREMENT OF FORCE-VELOCITY RELATIONSHIPS AND OPTIMAL LOADING FOR MAXIMIZING POWER IN OVER-GROUND SLED SPRINTING

Abstract

Aims. To determine whether force-velocity-power relationships can be accurately and reliably profiled using multiple trials of sled-resisted overground sprints. Furthermore, we sought to clarify and compare the optimal loading conditions for maximizing power production at peak velocity for recreational athletes and high-level sprinters.

Methods. Recreational mixed sport athletes [*N*=12] and sprinters [*N*=15] performed multiple trials of maximal sprints unloaded and towing a selection of sled loads (20-120% of body-mass). Velocity data were collected by a sports radar device, from which horizontal force and power measures developed at peak velocity were quantified using friction coefficients of the sled device and aerodynamic drag. Individual force-velocity and power-velocity relationships were fitted with linear and quadratic relationships, respectively. Accuracy of regression fits, mechanical and optimal loading variables (i.e. optimal force, optimal velocity and optimal normal load) were also calculated. The differences between groups were assessed using T-tests and magnitude based inferences (effect size [ES] and 90% confidence intervals). Test-retest reliability was assessed in nine recreational athletes who performed testing procedures 7 days apart.

Results. Force-velocity and power-velocity relationships were very well fitted with linear regressions and 2nd order polynomial equations, respectively, for both athlete subsets (mean R^2=0.997 and 0.977; P<0.001). The mean normal load that maximized peak power was 78±6 and 82±8% of body-mass (dependent on friction conditions), representing a resistance of 279±46 and 283±32 N at 4.19±0.19 and 4.90±0.18 m.s^{-1}, for recreational athletes and sprinters respectively. Compared to recreational athletes, sprinters displayed greater absolute and relative maximal power (17.2-26.5%; ES=0.97-2.13; P<0.02; *likely*), reminiscent of much greater velocity production (maximum theoretical velocity, 16.8%; ES=3.66; P<0.001;

most likely). Optimal force and normal-load did not clearly differentiate between groups (unclear and *likely* small differences; *P*>0.05), and sprinters developed maximal power at a much greater velocity (16.9%; ES=3.73; *P*<0.001; *most likely*). All mechanical variables were determined as reliable (ES=0.05-0.50; ICC=0.73-0.97; CV=1.0-5.4%).

Discussion and practical applications. Force-velocity-power relationships can be accurately profiled using common sled training equipment. Notably, the optimal conditions for maximizing peak power represent much greater resistance than current guidelines, and exist within a wide range among sprinters and mixed sport athletes. This method has potential value in quantifying individualized training parameters for optimized development of horizontal power, which may reflect greater increases in applied performance measures than those currently used and recommended in practice.

Introduction

The maximal power production ability of the human body has been studied extensively (Cormie et al., 2011a; Cormie, McGuigan, & Newton, 2011b), and its relationship to general athletic performance is well accepted in both research and applied communities (e.g. Suchomel et al., 2016). The mechanical capacity of a system for power production is represented in the force-velocity relationship (Fv), through which maximal power output may be enhanced by either increasing the ability to generate force output at low levels of velocity (i.e. force or strength dominated profile), maximize velocity at low levels of force (i.e. speed or velocity dominated profile), or both capacities (Morin & Samozino, 2016). The assessment of power and its mechanical determinants provides insight into the limits of the neuromuscular system for explosive performance (Samozino et al., 2014), and is valuable in sports featuring regular maximal exertion activities such as sprinting acceleration.

Traditionally, researchers have assessed ability of the lower limbs to produce power using multi-segmental lower limb exercise (e.g. cycling, jumping, explosive lower limb extension, and sprinting), with athletes performing repeated trials against a selection of progressively increasing resistance conditions (multiple-trial method) (e.g. Jaric, 2015). In the case of single extension a-cyclic movements, resistance is typically represented as external 'normal' loading added the body performing the movement (e.g. weighted barbell during a squat jump). In cyclic movements such as sprint cycling or sprint running, resistance is applied as friction force via braking systems (e.g. Jaskólska et al., 1999; Linossier et al., 1996). In these cases, force is represented with (Lakomy, 1985) or without (Vandewalle, Peres, Heller, et al., 1987) accounting for inertia, and is collected in tandem to velocity. The result are data corresponding to decreasing velocity (typically described in peak velocity attained each trial), with increasing resistive force (or load) and associated increased force production. The result is a linear force-velocity (Fv) relationship. 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. Power can be computed at any point as the integral of force and velocity ($P = F \cdot v$), with relationship between power and velocity (Pv) able to be fitted with quadratic equations (typically 2nd order polynomial) (Vandewalle, Peres, Heller, et al., 1987). The peak of the Pv relationship represents maximum power (P_{max}), otherwise

determined via the equation: $P_{max} = (F_0 \cdot v_0)/4$ (Samozino et al., 2012; Vandewalle, Peres, & Monod, 1987). P_{max} ability is widely considered a standard criterion of performance and measurement, and is coincidentally widely presented in variants of athlete groups and abilities.

An aim of multiple-trial power-profiling is determining the metrics that combine to present P_{max} (Soriano et al., 2015). Often termed 'optimal' variables (Linossier et al., 1996), these conditions are represented in optimal force (F_{opt}) and optimal velocity (v_{opt}) (see Figure 11). While determining P_{max} and optimal loading is useful for comparative analysis (Dorel et al., 2005), its value lies in specific training implementation. Particularly, the
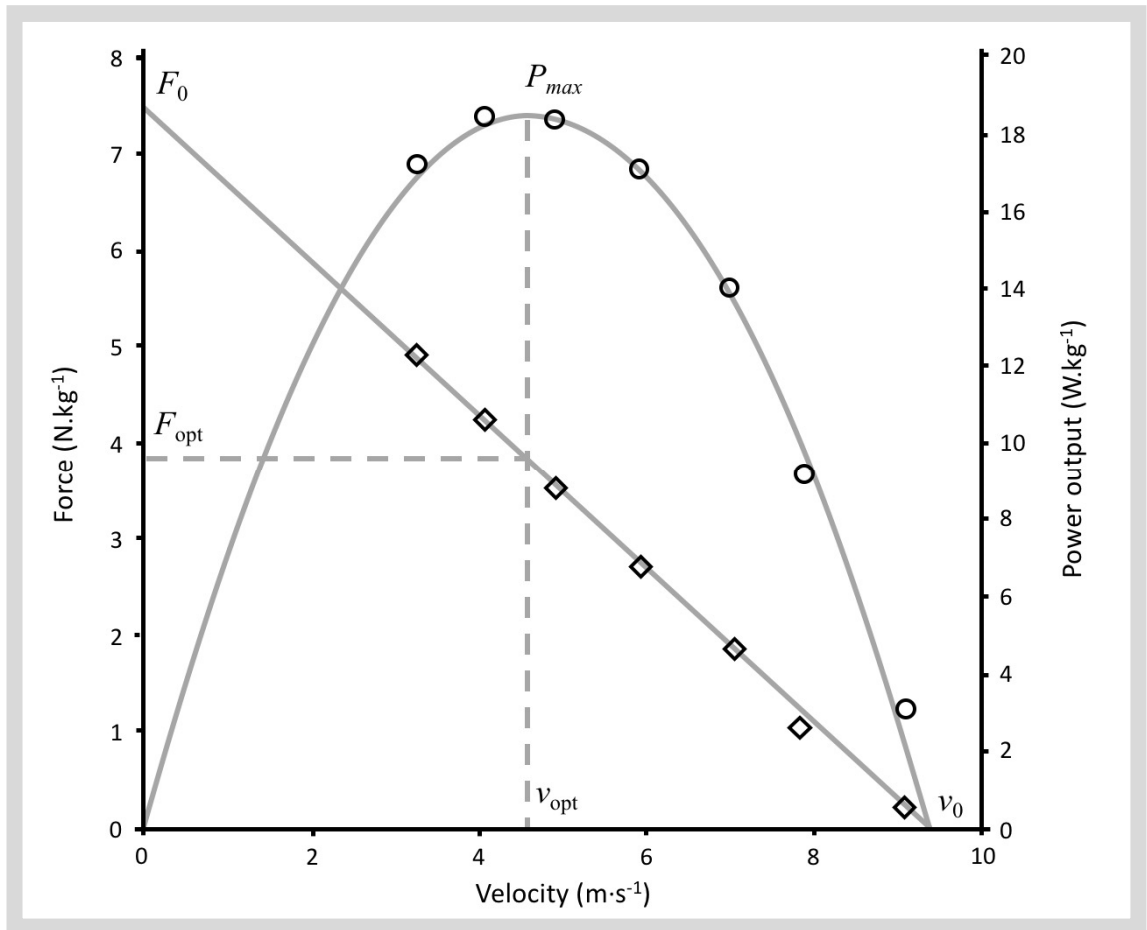
Figure 11. Graphical representation of the force-velocity and power-velocity relationship profiled via a multiple-trial method using resisted sleds.
Each data point represents values derived from a single individual trial at different loading protocols. F_0 and v_0 represent the y and x intercepts of 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 are shown.

performance monitoring, and application in actual competition scenarios in limited examples assessment of power using multiple resisted trials allows the operator to quantify an exact resistance protocol which can be easily integrated into training (if assessed in a specific environment) (Dorel et al., 2003; Hautier et al., 1996; Linossier et al., 1996). While there are few studies on the longitudinal effects of training around optimal conditions for power, it is generally viewed as a simple and effective means of training to improve P_{max} (Cormie et al., 2007; Kawamori & Haff, 2004; Soriano et al., 2015; Wilson et al., 1993). Furthermore, there is evidence to suggest benefits in a variety of neuromuscular and physiological capacitates (Beelen & Sargeant, 1991; Dorel et al., 2003; Francescato et al., 1995; McCartney et al., 1983; McDaniel et al., 2002; Neptune & Herzog, 1999; Sargeant et al., 1981), strengthening the rationale for profiling optimal loading characteristics where their inclusion in training is simple.

Until recently, most studies examining force-velocity-power (FvP) relationships in sprint running have done so using specialized sprint treadmill ergometers (e.g. Jaskólska et al., 1998). These methods require athletes to be tethered into place while driving a treadmill belt underneath them, with power calculated as the combination of belt velocity and horizontally oriented force (F_h), collected from tether mounted strain gauges (Lakomy, 1987). Based on the operational methods from cycling, athletes perform multiple sprints against increasing braking resistance to the belt (electromagnetic or motor-braking) (Jaskólska et al., 1998; Lakomy, 1987), after which individualized optimal load can be determined (Jaskólska et al., 1999). Three studies have examined optimal loading characteristics across multiple sprints (Andre, Fry, & Lane, 2013; Jaskólska et al., 1999; Jaskólski et al., 1996), although none calculated the exact conditions for maximal power with respect to plotting FvP relationships (Arsac et al., 1996). Moreover, given the dissimilarities between treadmill and overground sprinting (Morin & Seve, 2011), it is unknown whether training at optimal loads determined via these methods will transfer effectively to overground sprinting performance. In any case, very few athletes have access to this technology for training purposes, rendering assessment of optimal loading characteristics on treadmill ergometry of little value further than comparative analysis and monitoring.

While power profiling during overground sprinting have recently been shown possible (Rabita et al., 2015; Samozino et al., 2016), no attempt has been made to profile optimal

loading and mechanical variables using a multiple-trial resisted protocol during over-ground running. Despite the prevalence of resisted over-ground sprinting protocols in the literature (e.g. sprinting sleds, see Petrakos et al., 2016; Rumpf et al., 2015), the discussion of optimal loading modalities during over-ground sprinting typically involves comparatively light external loading protocols, selected to minimize kinematic alterations to unloaded sprinting technique (Alcaraz et al., 2009; Lockie et al., 2003). Therefore, the aims of this study were to: (1) assess whether a multiple-trial method, using resisted sprint sleds to supply resistance, could be used to accurately and reliably profile FvP relationships during over-ground sprinting; (2) quantify and present values of optimal loading for use for future researchers and practitioners and; (3) compare mechanical characteristics between sprint trained and recreational cohorts.

Methods

Subjects and protocol.

12 mixed sport athletes and 15 highly-trained sprinters (male; see Table 5) gave their written informed consent to participate in this study, which was approved by the Auckland University of Technology Ethics Committee (15/61). Mixed sport athletes were recreational level, and comprised of rugby union (*N*=5), soccer (*N*=3), American football (*N*=2), lacrosse (*N*=1), and martial arts (*N*=1). Sprint athletes were required to have attained a performance standard of at least 750 International Amateur Athletics Federation ranking points (Spiriev & Spiriev, 2014) in an event <400 m (see Appendix 4) within the previous season. This standard was selected as similar to the eligibility standards for the New Zealand national track and field championships (Athletics New Zealand, 2015). In addition, >2 years of sprint training experience were required, including >1 year using resisted sprint training methods. Primary events comprised of 100 m (*N*=10), 200 m (*N*=2) 400 m (*N*=1), 110 m (*N*=1) and 400 m hurdles (*N*=1). The two sprint athletes whose primary events were listed as 400 m (in addition to most others) met the performance criteria across *multiple* disciplines (e.g. 200 m and 400 m). The mean current (within 6 months) performance level of the group was 883±126 (mean±SD) IAAF points (range: 750-1152) in their primary event, with the sample including three current national champions and a national record holder. All athletes were

devoid of lower limb injuries (>3 months pre-testing). Athletes were either determined as familiar with the testing modality (i.e. had performed resisted sprinting with loads >50% of body-mass [BM]), or were provided with a familiarisation session, similar to that of the primary testing procedures, >72 hours pre-testing. Athletes were instructed to wear their typical footwear for maximal sprinting. Mixed sport athletes wore standard athletic footwear, and sprinters wore sprinting spikes. Before testing, athletes performed a standardized 20-30 min warm-up including jogging, dynamic stretching, technical drills, and submaximal 45 m stride outs (70, 80 and 90% of maximal self-selected effort). The testing protocol consisted of six to seven sprints up to maximal velocity ($v_{h_{max}}$), performed with increasing sled loading (0-120% of BM) on an indoor Mondo track surface. The testing was directly preceded by 5 min passive rest, and 5 min passive rest was prescribed between each trial.

Sample size calculation

Given there are no results published using this method, data on the reliability of the method was used to assess the inferential power of the study. Using a modified Excel spreadsheet to determined sample size for magnitude based inferences (xSampleSize.xls) (Hopkins, 2006a), a sample size of 27 was suggested for the clear assessment of small changes (ES=0.2). This was chosen as the default value of smallest worthwhile threshold according to Hopkins (2006a), being approximately equal to the within subject SD of 0.21 (determined from metrics of power).

Equipment

For resisted trials, a heavy duty sprint sled (5.64 kg; GetStrength, Model: HT 50 mm Sled, Auckland, NZ) was attached to a specialized harness (0.34 kg; XLR8, Model: SA1PM, Wellington, NZ; attachment point mid-low back), via a 3.3 m non-elastic nylon tether and high-tensile karabiners. The sled was engineered from folded stainless steel with smooth flat railings contacting the track surface (L×W: 45×30 cm, rail contact area: 265 cm²). A selection of calibrated Olympic style powerlifting plates (Model: PL Comp Discs, Eleiko Sport, Halmstad, SWE) were used to supply normal loading for the testing protocols, and were secured to the sled by a weightlifting collar. Athlete performance was measured throughout the sprint by means of a sports radar gun (Model: Stalker ATS II, Applied Concepts, Dallas, TX, USA), set on a heavy-duty tripod 5 m behind the athlete at a height approximating

Table 5. Descriptive characteristics of athlete cohorts

Characteristics	Recreational (*N*=12)			Sprinters (*N*=15)			Sprinters vs. Recreational		
	M	*±SD*	*Range (+/-)*	*M*	*±SD*	*Range (+/-)*	*Standardized difference (Cohens, 90% CI)*	*P-value*	*Rating*
Age (yr)	27	±4	(23; 34)	24	±4	(18; 34)	-1.22 (1.87; -0.57)	0.016	*Large**
Stature (m)	1.76	±0.08	(1.63; 1.90)	1.80	±0.04	(1.72; 1.86)	0.56 (-0.11; 1.22)	0.18	*Small**
Body-mass (kg)	82.5	±10.47	(65.3; 94.6)	78.1	±4.01	(71.3; 84.0)	-0.53 (-1.20; 0.15)	0.29	*Small**

Values are means ±SD and effect size (ES) with 90% confidence intervals (CI).

yr = age in years; m = meters; kg = kilograms.

Small, and large qualitative inferences: * likely, 75-94.9% when compared to recreational athletes.

COM (~1 m). The radar device was operated remotely via laptop to collect forward velocity-time data at a rate of 46.9 Hz. This device has been shown as valid and reliable for time-distance measurement (Chelly & Denis, 2001) Velocity-time data were collected via the manufacturer supplied 'STATS' software package (Model: Stalker ATS II Version 5.0.2.1, Applied Concepts, Dallas, TX, USA). Temperature (16.5±1.69°C) and barometric pressure (756±5 Torr) were recorded from each session from a portable weather unit to enable calculation of air density for further analyses.

Selection of loading and sprint distance

While pilot data suggested the load-velocity and force-velocity relationship to be linear, individualized loading calculated based on total bodily-mass (including shoes [0.56±0.11 kg] or sprinting spikes [0.40±0.06 kg], and harness) was decided as the best method of ensuring the peak and ascending limb of the power-velocity (Pv) curve were captured. Seven loading protocols were prescribed to provide a sufficient span of stimuli to promote peak power production (unloaded, 20, 40, 60, 80, 100 and 120% of BM). Weight-plates were applied to the sled as close as possible to the predetermined load respective of each condition. Any load over- or under- estimation (e.g. <400 g) was assumed negligible given the linearity of the regression fit shown in pilot testing. Regardless, exact loading was accounted for in subsequent equations. Loading was increased until a >50% decrement in unloaded $v_{h_{max}}$ and a visual peak of the parabolic Pv relationship was observed. This was monitored via a customised Excel spreadsheet which built approximated FvP relationships using raw unfiltered radar data from each sprint (see Appendix 7). All athletes performed sprints at 100% of BM (six protocols), with eight athletes requiring a trial at 120% BM. No athlete performed loading protocols greater than 120% due to the expected effects of fatigue. For each trial, the athlete would step up to a marked line on the track, take up all slack in the tether (lean into the sled), and sprint forward from a standing split stance without countermovement.

The distance sprinted was as follows: 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. Distances were selected from pilot data as an exaggeration of what was required to reach $v_{h_{max}}$. 45 m was the maximum useably distance allowed by the indoor track, was considered a great

enough distance to allow athletes to either reach or be within >95% of their absolute unloaded $v_{h_{max}}$. Athletes performed the sprints in the same lane of indoor Mondo track, in a running-lane marked with parallel cones in increments respective of the various trial distances. All athletes were verbally encouraged to present maximal involvement from the outset, and sprint 'through' each distance marker to ensure a full maximal collection devoid of any purposeful deceleration.

Data analysis

All velocity-time data collected via the STATS software were initially clipped at the point of deceleration (see Figure 12.), and were analysed using a custom made LabVIEW program (Build version: 14.0, National Instruments Corp., Austin, TX, USA), which was developed to fit the raw dataset with an exponential function, described below:

Application of exponential function

The velocity-time signal of a maximal sprinting trial is well described by a mono-exponential function (Furusawa et al., 1927; Volkov & Lapin, 1979), and this modelling has been regularly used in recent research (Cross et al., 2015; Mendiguchia et al., 2016; Samozino et al., 2016). In this method, the instantaneous velocity-time relationship is plotted via the following equation (Arsac & Locatelli, 2002):

$$v_h(t) = v_{h_{max}} \cdot (1 - e^{-t/\tau}) \tag{1}$$

where $v_{h_{max}}$ represents the maximal velocity reached during over-ground locomotion in m.s^{-1} and τ the acceleration time constant in seconds. Although this method is more common when modelling kinetics during acceleration (Samozino et al., 2016), its use was decided to decrease the noise in the velocity-time signal and present a more stable $v_{h_{max}}$ reading between trials. The mean fit of the exponential equation to all trials of radar data was R^2=0.999. From this point, composite 'multiple-trial' mechanical relationships are determined from kinetic variables calculated at the instant of $v_{h_{max}}$ for each trial, described below.

Mechanical data

The fundamental principles of dynamics in the horizontal direction enable the net horizontal antero-posterior GRFs to be modelled for the centre of mass (typically with respect to time).
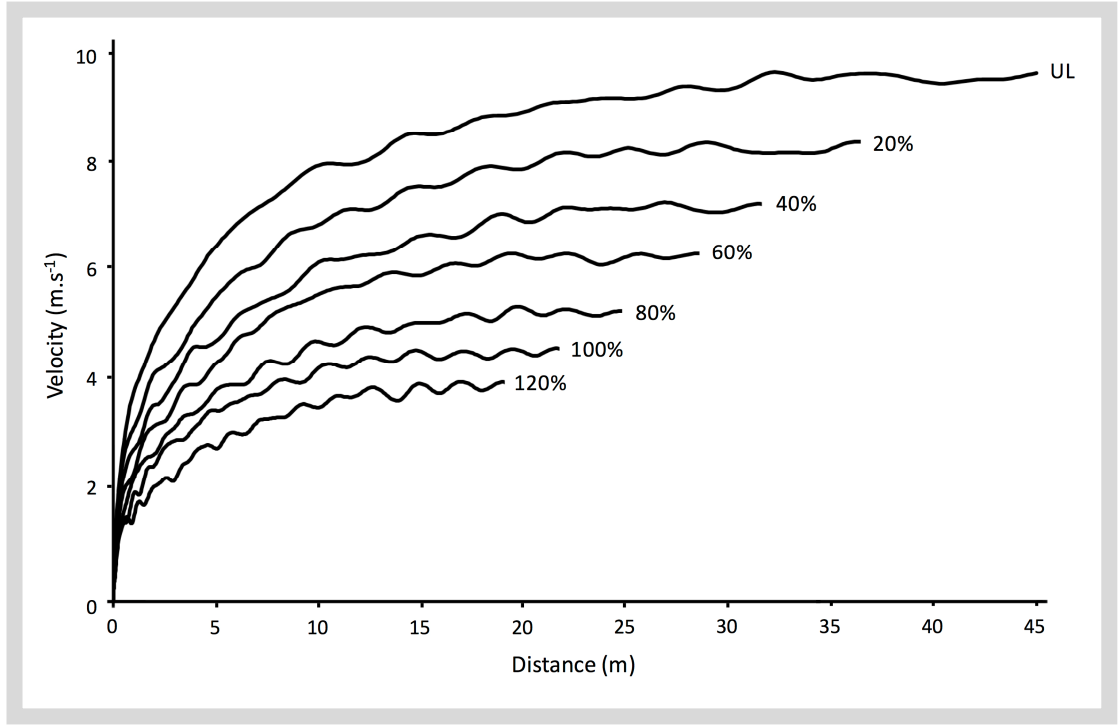
Figure 12. Graphical representation of the clipped raw velocity-distance radar data. Seven sled trials are pictured, clipped before deceleration occurred. From the trial with the highest $v_{h_{max}}$ (UL=unloaded sprint), the loading ranges from 20 - 120% of BM with each trial.

In the case of assessing these variables at $v_{h_{max}}$ it is assumed there is no acceleration occurring, therefore the equation represents:

$$F_{h_{peak}} = F_{aero} + F_f \tag{2}$$

with horizontal force at $v_{h_{max}}$ ($F_{h_{peak}}$) as equal to the sum of aerodynamic friction of the body in motion and kinetic friction force from the resisted sled (F_{aero} and F_f, respectively; see below sections).

Model of aerodynamic friction force (F_{aero})

Aerodynamic friction force can be estimated using the following equation:

$$F_{aero}(t) = k \cdot (v_h(t) - v_w)^2 \tag{3}$$

where v_w represents wind velocity (in m.s⁻¹) and k the athlete's coefficient of aerodynamic friction, calculated as the product of air density (ρ, kg.m³), frontal area of the runner (*Af*, in m²), and the drag coefficient of ambient air (Cd = 0.9; van Ingen Schenau, Jacobs, & de Koning, 1991):

$$k = 0.5 \cdot \rho \cdot Af \cdot Cd \tag{4}$$

with

$$\rho = \rho_0 \cdot \left(\frac{Pb}{760}\right) \cdot \left(\frac{273}{273+T°}\right) \qquad [5]$$

$$Af = (0.2025 \cdot h^{0.725} \cdot m^{0.425}) \cdot 0.266 \qquad [6]$$

where ρ_0=1.293 kg/m is the ρ at 760 Torr and 273 °K, *Pb* is the barometric pressure (in Torr), *T°* is the air temperature (in °C), and *h* is the athlete's stature (in m).

Model for kinetic friction force (F_f)

In order to determine the conversion of mass added to the sled to resistance experienced by the athlete, a sliding sled experiment was performed on the sprint-testing surface (for a detailed outline of the methods used to quantify these variables, see Chapter 3 of this thesis). In this experiment, a 9 kW mechanical winch device (Model: CMP100M Servo gear motor, SEW-Eurodrive, Auckland, NZ) was used to pull a common sprint sled, with a constant load (55.6 kg) and varying velocities, on the Mondo track. Normal loading (F_n) was compared against F_f at each velocity, resulting in a parabolic fit (Equation 8; Chapter 3). The following section serves as a summary of their application to sprinting performance in order to quantify net kinetic output, including correction for angle of pull (i.e. from the tether) to determine any vertical force occurring. F_f can be estimated using the following equation(s):

$$F_f = (\mu_k \cdot F_n)/(\cos\theta + \mu_k \sin\theta) \qquad [7]$$

where μ_k is equal to coefficient of kinetic friction, and F_n is the total weight of the sled (in Newtons, the total mass of the sled multiplied by acceleration due to gravity [-9.81 m.s^{-2}]). μ_k and angle of pull from the sled tether (θ) are estimated using the following equations:

$$\mu_k = -0.0052v_{h_{max}}{}^2 + 0.0559v_{h_{max}} + 0.3184 \qquad [8]$$

where μ_k is equal to a quadratic equation (see Chapter 3) including instantaneous velocity (in this case $v_{h_{max}}$). θ is estimated as:

$$\theta = Sin^{-1}((h_t)/c) \qquad [9]$$

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 $v_{h_{max}}$ ($P_{h_{peak}}$) can be calculated by the following equation:

$$P_{h_{peak}} = v_{h_{max}} \cdot F_{h_{peak}} \qquad [10]$$

with $F_{h_{peak}}$ calculated as described above. Fv and Pv relationships were generated for each

athlete from as a composite of athlete performance under each increasing loading condition (Lakomy, 1987). $F_{h_{peak}}$ and $P_{h_{peak}}$ were plotted against $v_{h_{max}}$ for each trial, and the compiled data were fitted with least-square linear and second-order polynomial regressions, respectively (Arsac et al., 1996). 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. Power at zero-x was assumed to be null. Maximum power was determined as the apex of the quadratic Pv relationship for each individual (P_{max}), and via a previously proposed and validated equation (i.e. $P_{max}2$) (Samozino et al., 2012; Vandewalle, Peres, Heller, et al., 1987):

$$P_{max}2 = (F_0 \cdot v_0)/4 \qquad\qquad [11]$$

Bias between P_{max} and $P_{max}2$ was calculated as the difference between the two variables, expressed as a percent of the reference value: $(P_{max} - P_{max}2)/P_{max}$. Optimum velocity ($v_{opt}$) and optimum force ($F_{opt}$) were identified as the levels of each respective variable at which peak power production occurred. Optimal normal loading (L_{opt}) was calculated via backwards conversion from F_{opt}, via the methods described above. In the case of F_{opt}, this includes any aerodynamic drag occurring at this stage of the sprint. Relative variables were determined by dividing the given absolute value by total system mass (e.g. body-mass with sled), and using the same processes described above to comprise a relative FvP composite relationship and associated variables.

Test re-test reproducibility of power and mechanical measurements

Inter-session test-retest reliability of all variables was assessed in 9 of the 12 mixed sport athletes, who performed two testing procedures separated by a 7 day period. Reassessment took place using the identical loading parameters to the first study ignoring any changes in body-mass (i.e. same loading protocols), at the same time of day to minimize diurnal fluctuations. Athletes were asked to standardize their activities around the testing (i.e. food, drink and activity).

Statistical analysis

Data were first assessed for outliers through visual assessment of box plots, where none were

found. Normality of distribution was assessed using the Sharpiro-Wilk test, and homogeneity between datasets by the *F*-Snedecor test. While some skewness and kurtosis was observed in the data, these values were typically within acceptable ranges (<2.0). Because of this factor, along with the dataset meeting other requirements for normality (Sharpiro-Wilk, *P*>0.05), parametric statistical methods were used. Additionally, analysis was performed on both raw data, and log transformed data, with no meaningful difference in outcome variables or interpretation. The resultant analysis from the raw dataset is presented for the reader.

Descriptive statistics are presented as means ± standard deviation (SD), and the range in raw units. Comparisons between subject groups were completed using magnitude-based inferences (MBIs) and independent samples T-tests (alpha criterion set at *P*<0.05). MBIs were calculated using a modified statistical Excel spreadsheet from sportsci.org (*xParallelGroupsTrial.xls*) (Hopkins, 2006b) using mixed sport athletes as the reference dataset, and the traditional statistics were calculated using a statistical software package (IBM SPSS Statistics 21, SPSS Inc., Chicago, IL). The classification of MBI thresholds used in this study were based on the operational methodology by Hopkins and colleagues (see sportsci.org) (Hopkins, Marshall, Batterham, & Hanin, 2009). Effect size (ES) and 90% confidence intervals (lower limit; upper limit) were calculated to compare the difference between two group means. Threshold values of 0.2, 0.6, 1.2, 2.0 and 4.0 were used to represent small, moderate, large, very large and extremely large effects, respectively, with the pre-set 0.2 used as the smallest worthwhile difference. Probabilities that differences were higher, lower or similar to the smallest worthwhile difference were evaluated qualitatively as: possibly, 25-74.9%; likely, 75-94.9%, very likely, 95-99.5%; most (extremely) likely, >99.5%. The true difference was assessed as unclear if the chance of both higher and lower values was >5%. Inter-test reliability of each variable was quantified by the coefficient of variation (CV in %), intra-class correlation (ICC), and the standardized change in the mean (ES; using threshold values described) between the two testing occasions (Hopkins, 2000).

Results

Tables 6 and 7 display the descriptive and between-groups comparative statistics for 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 in respect to the relationship from which they were determined. Where possible, values were also expressed as relative to BM. Table 8 presents test-retest reliability. For all cases in both athlete groups, Fv relationships were well fitted by linear regressions (R^2 ranging from 0.994 to 0.999 for sprinters and from 0.995 to 0.999 for mixed sport athletes, all $P<0.001$), and Pv relationships were well fitted by second-order polynomial regressions (R^2 ranging from 0.977 to 0.997 for sprinters and from 0.979 to 0.996 for mixed sport athletes; all $P<0.001$). A graphical example of mechanical characteristics are displayed in Figure 13, expressed as the mean of individual relationships for sprinters and recreational athletes. Appendices 8 and 9 show the fit and spread of all data for each of the cohorts.

Discussion

The results from this study show it is possible to compute composite FvP relationships with a multiple-trial protocol using sleds to provide external resistance. Accordingly, optimal loading parameters were able to be determined, with all athletes presenting values of much greater magnitude than currently recommended (Alcaraz et al., 2009; Lockie et al., 2003) and used (Petrakos et al., 2016) in sprint-training literature. The method exhibits high test-retest reliability, strengthening its applicability for profiling and training in the many sports that involve sprint running and a need for horizontal power development.

To the authors' knowledge, this study is the first of its type to investigate the ability to profile using a multiple-trial approach during over-ground sprint running. Overall, the results show mechanical relationships generated from multiple sled sprints are accurately fitted with linear (least square) and parabolic (2nd order polynomial) relationships, for Fv ($R^2=0.994$ to 0.999) and Pv ($R^2=0.977$ to 0.997), respectively, congruent with those observed in cycling (Seck et al., 1995; Vandewalle, Peres, Heller, et al., 1987), treadmill sprinting (Morin et al., 2010) and single-sprint over-ground methods (Samozino et al., 2016). We found the loading spectrum of 20-120% BM (including an unloaded sprint) provided sufficient stimuli to clearly establish the peak of the Pv parabolic relationship for the athlete and testing conditions, evidenced both in the significant R^2 values and visual fit of the data (i.e. one point lower than approximated v_{opt}). This is an important observation as profiling only part of the Fv relationship decreases the certainty with which P_{max} and mechanical variables are

Table 6. Summary of force-velocity results for recreational and sprint athletes

Mechanical Variables	Recreational (N=12)			Sprinters (N=15)			Sprinters vs. Recreational		
	M	$\pm SD$	Range (+/-)	M	$\pm SD$	Range (+/-)	Standardized difference (Cohens, 90% CI)	P-value	Rating
Force-velocity Relationship									
R^2	0.997	±0.0013	(0.995; 0.999)	0.997	±0.0016	(0.994; 0.999)			
P-value [a]	1E-08			1E-08					
v_0 (m·s^{-1})	8.35	±0.38	(7.53; 8.77)	9.75	±0.36	(9.19; 10.42)	3.66 (3.02; 4.31)	7E-10	V. large***
F_0 (N)	558	±92	(404; 707)	566	±63	(458; 667)	0.10 (-0.56; 0.76)	0.79	Trivial
$Rel\ F_0$ (N·kg^{-1})	6.63	±0.53	(6.00; 7.81)	7.25	±0.71	(6.15; 8.43)	0.97 (0.33; 1.60)	0.046	Moderate**
S_{Fv}	-66.6	±10.2	(-80.5; -49.1)	-57.9	±6.60	(-70.8; -46.7)	-0.96 (-1.62; -0.30)	0.014	Moderate**
L_0 (kg)	188.5	±31.68	(135.8; 239.4)	191.6	±21.3	(155.2; 226.3)	0.11 (-0.55;0.77)	0.779	Trivial
$Rel\ L_0$ (kg·kg^{-1})	2.28	±0.18	(2.04; 2.67)	2.45	±0.24	(2.08; 2.85)	0.80 (0.17;143)	0.105	Moderate*
Unloaded sprint									
v_{max} (m·s^{-1})	8.12	±0.37	(7.42; 8.58)	9.55	±0.29	(9.15; 10.17)	4.14 (3.49; 4.79)	5E-11	Extr. large***

Values are means ±SD and effect size (ES) with 90% confidence intervals (CI). [a] mean significance value of individual regression fits for each cohort.

Rel = relative to body-mass; v_0 = theoretical maximum velocity; F_0 = theoretical maximum force; S_{Fv} = slope of the linear force-velocity relationship; L_0 = theoretical maximum normal load; v_{max} = maximum velocity; m·s^{-1} = meters per second; kg = kilograms.

Trivial, small, moderate, very (V.) large, and extremely (Extr.) large qualitative inferences: * likely, 75-94.9%; ** very likely, 95-99.5%; *** most (extremely) likely, >99.5% effect, when compared to recreational athletes.

Table 7. Summary of power-velocity and optimal loading results for recreational and sprint athletes

Mechanical Variables	Recreational (*N*=12)			Sprinters (*N*=15)			Sprinters vs. Recreational		
	M	*±SD*	*Range (+/-)*	*M*	*±SD*	*Range (+/-)*	*Standardized difference (Cohens, 90% CI)*	*P-value*	*Rating*
Power-velocity Relationship									
R^2	0.989	±0.006	(0.979; 0.996)	0.987	±0.006	(0.977; 0.997)			
P-value [a]	2E-05			2E-05					
P_{max} (W)	1161	±223	(458; 667)	1361	±171	(1097; 1601)	0.97 (0.32; 1.62)	0.017	Moderate**
Rel P_{max} (W·kg^{-1})	13.77	±1.48	(11.73; 17.17)	17.41	±1.81	(14.06; 20.31)	2.13 (1.50; 2.77)	4E-05	V. large***
$P_{max}2$ (W)	1168	±222	(458; 667)	1381	±170	(1120; 1624)	1.04 (0.39; 1.69)	0.011	Moderate**
Rel $P_{max}2$ (W.kg^{-1})	13.85	±1.46	(11.86; 17.12)	17.67	±1.80	(14.36; 20.59)	2.26 (1.62; 2.89)	2E-05	V. large*
Bias (%) [b]	0.59	±0.71	(-0.64; 1.50)	1.50	±0.58	(0.11; 2.15)			
Optimal loading conditions									
F_{opt} (N)	279	±46	(202; 354)	283	±32	(229; 333)	0.09 (-0.57; 0.75)	0.81	Trivial
Rel F_{opt} (N.kg^{-1})	3.37	±0.26	(3.02; 3.95)	3.62	±0.36	(3.07; 4.21)	0.77 (0.13; 1.40)	0.12	Moderate*
v_{opt} (m.s^{-1})	4.19	±0.19	(3.78; 4.39)	4.90	±0.18	(4.62; 5.23)	3.73 (3.09; 4.37)	5E-10	V. large***
L_{opt} (kg)	64.4	±11.0	(46.0; 81.6)	64.2	±7.3	(51.8; 76.5)	-0.01 (-0.67; 0.64)	0.783	Trivial
Rel L_{opt} (kg.kg^{-1})	78	±6	(69; 91)	82	±8	(70; 96)	0.59 (-0.04; 1.22)	0.118	Small*

Values are means ±SD and effect size (ES) with 90% confidence intervals (CI). [a] mean significance value of individual regression fits for each cohort; [b] percent bias between P_{max} and $P_{max}2$ for each cohort.

Rel = relative to body mass; v_{opt} = velocity at peak power production; 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; L_{opt} = normal loading at peak power production; m·s^{-1} = meters per second; W = Watt; N = Newton; kg = kilogramme. Trivial, small, moderate, and very large (V. large) qualitative inferences: * likely, 75-94.9%; ** very likely, 95-99.5%; *** most (extremely) likely, >99.5% effect, when compared to recreational athletes.

Table 8. Reliability of sled-resisted multiple trial method

Mechanical Variables	Reliability (N=9)		
	Change (ES)	*CV%*	*ICC*
Force-velocity Relationship			
v_0 (m·s^{-1})	*Small* (0.5)	1.1	0.92
F_0 (N)	*Trivial* (0.17)	4.6	0.95
Rel F_0 (N·kg^{-1})	*Small* (0.43)	4.5	0.73
S_{Fv}	*Trivial* (0.18)	5.4	0.91
L_0 (kg)	*Trivial* (0.13)	4.7	0.97
Rel L_0 (kg·kg^{-1})	*Trivial* (0.20)	3.4	0.91
Power-velocity Relationship			
P_{max} (W)	*Trivial* (0.15)	4.0	0.97
Rel P_{max} (W·kg^{-1})	*Small* (0.33)	4.0	0.88
$P_{max}2$ (W)	*Trivial* (0.15)	3.9	0.98
Rel $P_{max}2$ (W.kg^{-1})	*Small* (0.34)	3.9	0.88
F_{opt} (N)	*Trivial* (0.17)	4.6	0.95
Rel F_{opt} (N.kg^{-1})	Small (0.30)	3.3	0.78
v_{opt} (m.s^{-1})	*Trivial* (0.05)	1.0	0.93
L_{opt} (kg)	*Trivial* (0.17)	4.8	0.95
Rel L_{opt} (kg.kg^{-1})	*Small* (0.47)	4.9	0.68
Unloaded sprint			
$v_{h_{max}}$ (m·s^{-1})	*Trivial* (0.0)	1.4	0.90

Values are change scores between sessions in standardized effect (effect size), coefficient of variation (CV%), and intraclass correlation coefficient (ICC).

v_0 = theoretical maximum velocity; F_0 = theoretical maximum force; *Rel* = relative to body mass; S_{Fv} = slope of the linear force-velocity relationship; P_{max} = peak power production determined from the apex of the power-velocity relationship; 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} = meters per second; N = Newton; W = Watt; kg = kilogramme.
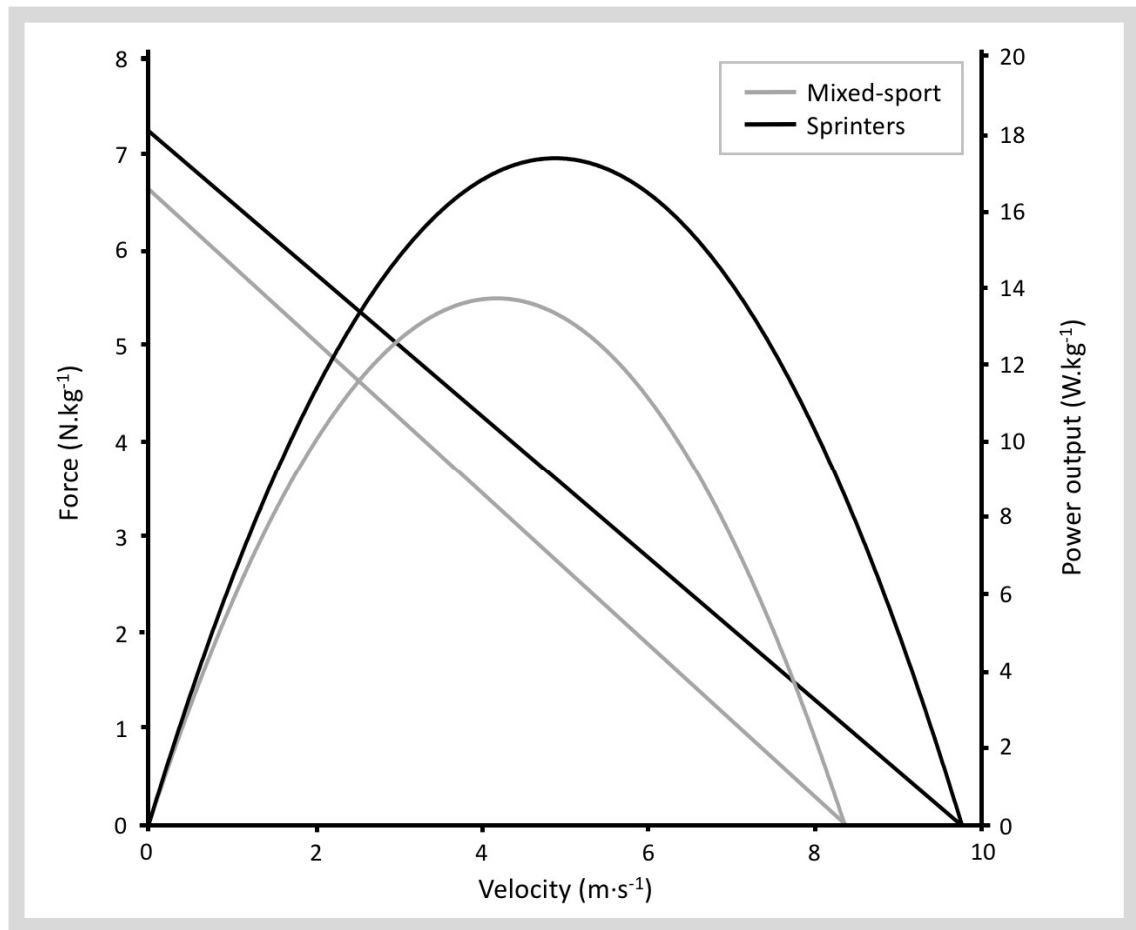
Figure 13. Mean of individual force-velocity-power profiles of mixed sport athletes (grey lines), compared to sprinters (black lines).

determined. Of note, it is possible that other athletes, and testing conditions (i.e. friction coefficients) may require greater or lesser protocols to capture the instant of P_{max}. The bias observed between P_{max} and $P_{max}2$, determined via the linear Fv relationship from a validated equation (Samozino et al., 2016; Samozino et al., 2012; Vandewalle, Peres, Heller, et al., 1987) was minimal in both groups (0.6-1.5%), suggesting P_{max} may be accurately determined from the linear Fv relationship using a lower number of sprints than the current study (Jaric, 2016).

No research has presented optimal loading conditions determined from FvP profiling for sprint running. Subsequently, although resisted sprint training is increasing in popularity, there is currently little mechanical evidence supporting the selection of loads for training implementation. In association with the well plotted FvP relationships, the results from this study show the mean F_{opt} to be 3.37 and 3.62 N.kg⁻¹, equal to 78 and 82% BM (i.e. L_{opt} for the present friction conditions), at 4.19 and 4.90 m.s⁻¹ (recreational vs. sprinters,

respectively). Optimal resistance was reported by Jaskólski et al. (1996) and (Jaskólska et al., 1999) as a variable resistance (i.e. torque applied to the belt) of approximately ~137-203 N (10.1-15% as a range of maximal inbuilt braking resistance) for a mixed population, which is somewhat lower than the absolute force observed in the current study for recreational mixed-sport athletes (Mean=279 N). This could be due to inaccurate calculation of optimal loading (i.e. not from FvP relationships and regression equations), dissimilarities in running action compared to overground sprinting, individual technical or physical capabilities of the cohorts (recreational students, cyclists and power athletes vs. mixed sport athletes), or a combination of factors. Optimal loading conditions existed within a wide range for both cohorts, although this seems logical given these conditions are intrinsically linked to the technical and mechanical Fv characteristics of each athlete subset (Morin & Samozino, 2016).

The multiple sprint method accurately profiled mixed sport and well-trained sprinters alike (R^2=0.977-0.999; P<0.001), highlighting its value and applicability to a wide range of athletes. Comparisons between athlete subsets showed sprinters exhibited greater P_{max} capacity (18.3%; ES=0.97; P<0.05; *very likely*), particularly when expressed as relative to BM (26.4%; ES=2.13; P<0.001; *most likely*), than recreational athletes. Similarly to the findings of Jaskólska et al. (1998) where velocity dominant athletes towed the spectrum of lighter loads faster, sprinters displayed a much greater v_0 capacity than their recreational counterparts (16.8%; ES=3.66; P<0.001; *most likely*). While differences in absolute force capacities were unclear, sprinters displayed moderately greater capacity when expressed as relative to BM (9.4%; ES=0.97; P<0.05; *likely*), which may explain the unclear and otherwise non-significant differences in optimal force and loading characteristics. Note that in the case of relative F_{opt} and relative L_{opt}, while the differences were *likely* moderate and small (respectively), they did not meet the alpha criterion for statistical significance (P>0.05, resultant of the wide ranges in the values in both cohorts; see Appendices 8 and 9 for a composite graph of the range in individual athlete FvP characteristics). Whether these ranges are due to the somewhat non-homogenous selection of athletes (mixed sport, and sub-elite sprinters – both with mixed training backgrounds), or an accurate representation of the spread in physical capacities expected within a population, requires more investigation. There was a very large and clear effect, however, in the velocity at which the sprinters generated

P_{max} (16.9%; ES=3.73; $P<0.001$; *most likely*). Note that these results are to be expected, given optimal capacities are intrinsically related to maximal mechanical capacities (i.e. $0.5 \times F_0$ or v_0). These results appear to align with recent literature (Morin et al., 2010; Morin et al., 2015; Rabita et al., 2015) highlighting the ability to produce force at greater velocities characterizes well-trained sprinters, rather than absolute force production ability. Given literature (Cross et al., 2015) has suggested that mechanical capacity for force at low velocities might be key to performance in acceleration based contact sports, we would hypothesize that such athletes (e.g. rugby forwards) would generate P_{max} at lower velocities than the averages seen in this study. Separation of these data strings from the overall dataset would seem to support this assumption, with the rugby players from the mixed sport cohort (N=5) generating a v_{opt} of 4.25±0.26 m.s^{-1}, and an F_{opt} of 323±23 N (-13.3 lesser and 13.9% greater than sprinters, respectively). Relative F_{opt} (3.50±0.29) and L_{opt} (81.1±6.4%) present very similar values (-3.3 and -1.2%, respectively), which may suggest a requirement for absolute force output in contact scenarios (Cross et al., 2015). These data are only speculative, and future research should aim to determine optimal loading characteristics of force dominant athletes, and better profile contrasting athlete cohorts.

Recent studies (Morin, Edouard, et al., 2011; Morin et al., 2015; Rabita et al., 2015) have left no doubt that the determinants of sprinting ability are both the absolute physical capability of the body, and technical ability to apply this raw capacity in an effective manner. In the effort of preserving the latter skill, studies featuring resisted sprinting have typically used or promoted protocols reminiscent of those that avoid significant deviations from unloaded sprinting mechanics in both the maximal velocity and acceleration phases (7.5-15.5% decrements in velocity; ~7-20% of BM (Alcaraz et al., 2009; Clark, Stearne, Walts, & Miller, 2010; Harrison & Bourke, 2009; Lockie et al., 2003; Luteberget, Raastad, Seynnes, & Spencer, 2014; Makaruk, Sozański, Makaruk, & Sacewicz, 2013; Spinks, Murphy, Spinks, & Lockie, 2007; West et al., 2013; Zafeiridis, Saraslanidis, Manou, & Ioakimidis, 2005). It seems logical that the articles adhering to these methods have typically reported similar performance outcomes for resisted vs. un-resisted training protocols; albeit a consensus in favour of the use of sled training (Petrakos et al., 2016). The results from this study, in association with the results from research examining the kinetics of heavier loading protocols (20-43% of BM) (Cottle, Carlson, & Lawrence, 2014; Kawamori, Newton, & Nosaka,

2014), suggest loading selection based on minimizing kinematic alterations does not provide an effective stimulus for maximizing horizontal power production. Even the lowest case of optimal loading determined by an individual in this study (69% BM, or a ~50% velocity decrement from unloaded sprint) greatly exceeds the range of ~7-43% BM commonly used for testing and training (Petrakos et al., 2016). While practicing within these ranges of loading may still provide beneficial stimuli for a particular goal, such as development of horizontal force capacity during late acceleration, blanket adherence to these guidelines is not recommended for all performance outcomes. It should be noted that although acute alterations to technique were not measured in this study, given evidence to suggest substantial deterioration occurs below ~90-95% of maximal velocity (e.g. Kivi, Maraj, & Gervais, 2002) it was assumed all loads used would significantly affect sprinting technique. The methods used in this study should be considered as a movement-specific horizontal power stimulus that may improve the physical and technical capacities underlying sprinting performance (Morin, Edouard, et al., 2011; Morin et al., 2015).

Given that sprinting acceleration appears highly linked to measures of maximal horizontal power (Morin et al., 2012; Morin et al., 2015; Rabita et al., 2015), it is plausible that implementing power dominant training may elicit increases in these performance measures. Nevertheless, while greater benefits might be expected from training at or close to optimal load, further research and testing is necessary to determine whether worthwhile and timely adaptations are observed in various athlete subsets, and whether training of this nature effects other performance capacities that may be key to success in some athlete codes (i.e. maximal velocity phase). Moreover, given ballistic performance in jumping has been shown to be affected by not only $P_{\max}$ ability but also S_{Fv}, it is possible that training at either extreme of the Fv relationship may enhance performance by aligning the subject to their 'optimal' profile (Samozino et al.). For example, an athlete requiring improvement in velocity capacity may practice assisted-light sled loading (i.e. less than L_{opt}), and an athlete requiring improvement in force capacities may practice heavy sled loading (i.e. greater than L_{opt}, or >69-96% BM). In any case, sled training should factor as part of a periodized holistic program including varying degrees of technical, unloaded, resisted and assisted sprint work and general conditioning practices. Practically, concerns of technical alterations resultant of optimally loaded sled training could be mitigated by intelligent programming, where emphasis is placed

on multiple capacities in the effort of producing a well-rounded program targeting multiple factors of sprinting performance.

The method used to quantify mechanical capabilities intrinsically shapes the interpretation of output variables. The current work uses methods from early sprint cycling studies (Vandewalle, Peres, Heller, et al., 1987), with optimal loading conditions computed at the instance of $v_{h_{max}}$. Practically, these techniques may be integrated into training by having an athlete build to maximal (optimally resisted) velocity, and maintain maximum effort for an extended period of time (e.g. ~3-5 s). While not researched in sprint running, these methods have been shown to benefit cycling (Beelen & Sargeant, 1991; Dorel et al., 2003; Francescato et al., 1995; McCartney et al., 1983; McDaniel et al., 2002; Sargeant et al., 1981). Given the multiple-trial relationship represents the span of the athlete ability to produce force and velocity with impeding resistance, similarly to that of the force required for acceleration during an unloaded sprint (Morin et al., 2015), training in this manner should present positive changes in unloaded sprinting performance. Training with loads reminiscent of P_{max} should shift the Fv curve to the right (Samozino et al., 2014; Samozino et al., 2012), and present an overall increase in global power production. However, given this is the first study of its kind, it is unknown how the variables developed from a single- and multiple-trial method overground compare, and what the training outcomes would be observed on mechanical capacities and general sprinting performance.

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 this may have affected the ability to apply force through increased friction (or other factors with regards 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 subject group. It would have been unrealistic for mixed sport athletes to wear sprinting spikes and become familiar with their use in a single session. Progressive, non-randomized application of loading was used in this procedure as per previous FvP studies (e.g. Jaskólska et al., 1998; Vandewalle, Peres, Heller, et al., 1987), which may have affected the results observed reminiscent of

potentiation or fatigue. Non-randomized loading was selected for two primary reasons: 1) measureable increments were necessary to determine the point at which to cease the testing protocol (as per previous research); and 2) it was determined during pilot testing that performance was extremely variable without athletes being able to cue the resistance from the protocol directly preceding it.

Practical Applications

- 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.

- Optimal loading conditions are much greater than currently used in the literature (L_{opt} of 78-82% vs. <43% of BM, and v_{opt} of 48-50% vs. <30% decrement of $v_{h_{max}}$), highlighting practitioners and researchers should reconsider the guidelines on which they implement sled sprints and similar resisted sprint modalities. Future studies should look to use resistance of these magnitudes to assess the longitudinal effects of optimally loaded sprints on horizontal power and sprinting performance.

- Future studies should quantify optimal loading characteristics for other athlete groups. Particularly, acceleration and force dominant populations (e.g. high level rugby players) would offer an interesting juxtaposition to the velocity-dominant sprinters profiled in this study.

- The wide range of optimal loading characteristics (e.g. 69-96% BM) observed in this study indicate the need for individualized training zones among both recreational and high-trained sprint athletes. Further research is necessary.

Performance Centre (HPC) who were willing give their time and best effort in the interest of furthering the area of sprinting research.

CHAPTER 5

A SIMPLIFIED METHOD FOR THE ASSESSMENT OF OPTIMAL LOADING FOR SLED RESISTED SPRINTING

Preface

This chapter focuses on the calculation of mechanical and optimal loading conditions from two methods, drawing together the information from previous chapters. Specifically, this chapter describes the differences in mechanical characteristics determined via a multiple trial sled method, to that determined from a single unloaded sprint. A primary goal for this Chapter was to determine whether a single sprint could be used to assess optimal sled loading for practical implementation into training.

Note: The operating procedures, excluding those referring to the 'single trial method', are very similar to those detailed in Chapter 4 of this thesis. Subsequently, what follows is a truncated summary of the procedure to aid in reader contextual understanding. Full lists of procedures and equations can be found in Chapter 2, Table 3 (single sprint method), Chapter 3 Equations 1 through 4 (friction calculations), and Chapter 4 Equations 1 through 13 (multiple sprint).

Abstract

Summary The aim of this study was to ascertain whether optimal sled loading for maximizing power could be calculated from a single sprint. Further, we sought to compare force-velocity and optimal loading conditions between a single unloaded sprint and a multiple trial method.

Methods 27 healthy mixed-code athletes performed five to six maximal velocity sprints towing a sled, loaded with a selection of masses (20-120% of body-mass), and an unloaded sprint on an athletics track. For each trial, force and power were determined at maximum velocity (assessed via radar), from pre-determined friction force coefficients and aerodynamic drag. Individual linear force-velocity and parabolic power-velocity relationships, and

associated mechanical variables and optimal loading conditions were generated using data from each trial. Least squares linear and quadratic regression fits, mean and the range of outcome mechanical variables were calculated. A second method of analysis, drew the same variables from a single unloaded sprint using an inverse dynamics method. Methods were compared using regression analysis and absolute bias (±90% confidence intervals). Strength of agreement was assessed using the Pearson product-moment correlation coefficient, and the magnitude of error, expressed in the typical error of estimate (TEE) in standardized units (effect size [ES]).

Results The average relative bias between the methods was between 0.4 and 7.3% in favour of the single trial method. Power and maximal force criterions showed strong correlations between methods (r=0.71-0.86), although the typical error similarly ranged from moderate to large (TEE=0.53-0.71). Similar trends were observed in relative and absolute optimal force (r=0.50-0.72; TEE=0.71-0.88), with estimated optimal normal loading relatively incomparable (bias=0.78-5.42 kg; r=0.70; TEE=0.73). However maximal velocity, and associated optimal velocity, were near identical between the methods (r=0.99), with little bias (0.4-1.4% or 0.00-0.04 $m.s^{-1}$) and error (TEE=0.12).

Discussion and practical applications While the force-velocity-power characteristics from both methods were similar, large error was associated with determining optimal force and normal loading from a single sprint. Optimal velocity was extremely well matched between methods, suggesting practitioners could use a single sprint to accurately determine the velocity for maximizing power in sled sprinting. These findings provide the basis for easy implementation of these methods into regular testing, for subsequent increased individualization of training.

Introduction

The assessment of power production and its determinants is common in sports science practice (Cormie et al., 2011b). The capacity for power can be evaluated through the force-velocity (Fv) relationship, which determines the balance between the mechanical factors underlying the expression of power during explosive movement (Morin & Samozino, 2016). Given the links between measures of power and athletic performance (Cronin & Hansen, 2005), enhancing power is a goal of many training interventions. Consequently, quantifying the metrics that maximize power production is of value, as training at or around maximal power may lead to enhanced adaptations (Cormie et al., 2007; Wilson et al., 1993). The usefulness of this information, however, is ultimately dependent on the modality of assessment and its subsequent ease of implementation into training.

Fv profiling typically follows one of two methods: repeated trials against a selection of increasing resistance conditions (multiple trial method) (Vandewalle, Peres, Heller, et al., 1987), or during a single trial of cyclic acceleration (Seck et al., 1995). Both cases have been shown to provide linear Fv relationships, and parabolic power-velocity (Pv) relationships in a range of acyclic (e.g. jumping or throwing) and cyclic (e.g. cycling and sprint running) movements (Jaric, 2015). In the case of the multiple sprint method, resistance is provided for each trial via application of vertical or 'normal' loading (single extension movements) (Samozino et al., 2010), or friction from braking systems (sprinting accelerations on cycle or treadmill ergometers) (e.g. Jaskólska et al., 1999). Either force, torque or mass are recorded for each trial and compiled into a single relationship of decreasing velocity with increasing resistance. In the case of cyclic movements (e.g. sprint cycling or running), the same relationship can be profiled during a single bout of maximal acceleration by plotting increasing velocity against decreasing force. The single trial method provides value to practitioners wishing to minimize assessment time and the physical impact on the athlete. Not only have researchers shown Fv profiling is possible during sprint running on treadmills using both multiple trial (Jaskólska et al., 1998) and single trial methods (Morin et al., 2010), but recent evidence has shown these approaches are possible during overground sprinting (for multiple trial method see chapter 4, and for single sprint method see Samozino et al., 2016). Of note, a recently validated field method has been shown to provide accurate and repeatable Fv relationships and associated mechanical variables using inverse dynamics

applied to simple velocity-time data of a single sprint acceleration (Samozino et al., 2016). This simple method can be applied to data from common non-specialist field-testing equipment, such as photovoltaic timing gates (Samozino et al., 2016), sports radar (Cross et al., 2015), lasers (Buchheit et al., 2014), and global positioning systems (Nagahara et al., 2016), making assessment of these mechanical characteristics accessible to many practitioners.

Plotting the Fv relationship allows the conditions under which maximal power (P_{max}) occurs to be quantified. Termed optimal force (F_{opt}) and optimal velocity (v_{opt}), the assessment of these variables is common within jumping and cycling literature (Jaric, 2015; Soriano et al., 2015), due to theory and evidence suggesting training replicated in these conditions will maximize power adaptations (Cormie et al., 2007; Kawamori & Haff, 2004; Wilson et al., 1993). The multiple trial method is common in this respect, as optimal loading conditions can be easily quantified based on the magnitude of normal load added to each respective trial. While these variables can be determined similarly using a single trial (e.g. Cross et al., 2015; Hautier et al., 1996), the actual usability and implementation of these variables is limited due to the lack of practical training load associated with their calculation. In other words, while these conditions assessed on ergometers may allow optimal resistance to be approximated via regression equation (e.g. a friction loaded cycle), methods that use un-resisted conditions (e.g. overground sprinting) render the assessment of useable optimal loading parameters more complex. Simply, without an ability to translate F_{opt}, and v_{opt} into training or competition (see Dorel et al., 2005), they represent little value further than additional comparative analysis. In the previous chapter it was shown possible to profile accurate FvP characteristics and optimal loading conditions using six to seven trials of sled-resisted sprints compiled into a single relationship. While F_{opt} and v_{opt} can be similarly calculated from a single overground sprint (Cross et al., 2015), it is unknown whether these variables are similar or well predicted to those determined via a multiple sprint effort. Given the ease of implementation of such assessment techniques (Mendiguchia et al., 2016), determining the validity for assessing optimal sled-resisted sprint loading could present a significant advancement in the individualization of training load.

The aim of this study was to compare the mechanical data determined via a validated single sprint approach to a multiple sled-resisted method, and ascertain whether a simplified

method could be used to calculate optimal loading conditions.

Methods

Subjects and protocol

Ethical approval was provided by the Auckland University of Technology Ethics Committee (15/61). 27 athletes from mixed sporting backgrounds, training histories and performance levels (see Chapter 4, Table 7 for split cohorts) participated in this study. The sample included sprinters (*N*=15), and a range of recreational level athletes (*N*=12), combined to provide a relatively non-homogenous cohort to better assess validity. All athletes were uninjured (>3 months pre-testing), and familiar with the testing procedures. Athletes were allowed to wear whatever footwear they generally perform maximal sprinting efforts in, resulting in sprinters wearing spikes and recreational athletes wearing standard athletic footwear. Following a detailed warm-up protocol, athletes performed one unloaded sprint followed by 5 or 6 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.

Equipment

To provide resistance, athletes were harnessed (0.34 kg; XLR8, Model: SA1PM, Wellington, NZ; attachment point mid-low back via a 3.3 m non-elastic nylon tether) to a heavy duty sprint sled (5.64 kg; GetStrength, Model: HT 50 mm Sled, Auckland, NZ) loaded with a selection of calibrated powerlifting 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 at 5 m at a height of 1 m, collecting outward bound information at 46.9 Hz. Velocity-time data were collected using the manufacturer supplied software.

Loading selection and sprint distance

A maximum of seven loading protocols were prescribed to provide a sufficient span of stimuli to promote peak power production (unloaded, 20, 40, 60, 80, 100 and 120% of BM).

Following an unloaded sprint, loading was increased until greater than a 50% decrement in unloaded $v_{h_{max}}$ and a visual peak of the parabolic Pv relationship was observed. Athletes performed maximal sprints on a marked Mondo athletics track, under the following 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.

Data Analysis

Two main methods of analysis were used for this study: 1) the analysis and compilation of Fv values from each of the resisted trials into a single composite relationship (i.e. multiple trial method); and 2) the assessment of instantaneous Fv during the acceleration phase of the initial single unloaded sprint (single trial method). In both cases the raw velocity-time data of all trials were fit with a mono-exponential function (Furusawa et al., 1927; Volkov & Lapin, 1979). Both analysis processes were completed using separate pathways of a custom LabVIEW platform (Build version: 14.0, National Instruments Corp., Austin, TX, USA), used in previous research (Cross et al., 2015; Mendiguchia et al., 2016).

Single Sprint method

External kinetics and kinematics were modelled from centre of mass movement via the application of a macroscopic inverse dynamic model (Furusawa et al., 1927; Helene & Yamashita, 2010), representing averaged values across contact and flight times. This method has been described in significant detail by Samozino et al. (2016), who validated the approach against an in-ground force-plate system. Briefly, the acceleration and horizontal orientation of the athlete's COM can be conveyed after integration and derivation of velocity (v_h) over time, enabling the net horizontal antero-posterior GRF (F_h) to be modelled. This approach considers the mass (m) of the athlete performing the sprint in determining F_h over time in association horizontal acceleration, with the addition of aerodynamic friction force (F_{aero}). Mean net horizontal antero-posterior power output (P_h) is then modelled at each instant as the product of F_h and v_h: $P_h = F_h \cdot v_h$

Multiple Sprint method

The multiple sprint method derives from the same fundamental principles of dynamics, however in this case because variables were quantified at peak velocity during each trail ($v_{h_{max}}$), it was assumed zero acceleration was occurring. Therefore, in this instance F_h was equal to the sum of F_{aero} and kinetic friction force (F_f) from the resisted sled. F_{aero} was determined via the same methods used in the single trial method, and F_f was calculated using the coefficient of friction, mass added to the sled, instantaneous velocity and angle of pull between the athlete and the sled (for full details see Chapter 3). P_h at $v_{h_{max}}$ for each trial was modelled as: $P_{h_{peak}} = F_{h_{peak}} \cdot v_{h_{max}}$.

FvP relationships and optimal loading conditions

Fv and Pv relationships were generated for each athlete using both single and multiple trial methods. For both methods, P_h and v_h were plotted against each other under least-squares linear regressions, and P_h and v_h we plotted to comprise quadratic equations under 2nd order polynomial fits (Hintzy et al., 1999; Samozino et al., 2016). In the case of the single trial method, this comprised of instantaneous values throughout acceleration, 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 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}, respective of the FvP relationships determined for each method. L_{opt} was calculated via previously outlined methods, integrating friction force calculations, from the values of v_{opt} and F_{opt} (and F_{aero}) assessed from each respective method. Relative variables were determined by dividing the given absolute value by body-mass.

Statistical analysis

Data were assessed for outliers, normality of distribution and homogeneity. Having sufficiently met assumptions, parametric statistics were used on the raw datasets.

Descriptive statistics are presented as means ± standard deviation (SD). Validity comparisons between the multiple sprint and single sprint method used linear regressions and absolute bias ±90% confidence intervals. This approach was selected due to evidence suggesting systematic bias towards the compared condition versus the criterion in more traditional methods (Hopkins, 2004). Strength of agreement was assessed using Pearson's correlation (r), and the following interpretations: 0.3, 0.5, 0.7, 0.9, and 1.0, to represent weak, moderate, strong, very strong and perfect relationships, respectively. The magnitude of error, expressed in the typical error of estimate in standardized units (effect size [ES]), using a modified Cohen's scale to interpret: 0.1, 0.3, 0.6, and >0.6 to represent trivial, small, moderate, and large, respectively. Validity statistics were calculated using a modified statistical Excel spreadsheet from sportsci.org (*xvalid.xls*) (Hopkins, 2015) using the multiple trial method as the criterion. Thresholds used in this study were based on the operational methodology by Hopkins and colleagues (see sportsci.org) (Hopkins et al., 2009).

Results

See Table 9 for full description of results from analyses. The average relative bias between the methods was between 0.4 and 7.3% in favour of the single trial method. Moderate to very strong correlations were present, however the typical error ranged from small to large. v_0 and v_{opt} were the most comparable between the methods (very strong correlations), with the single trial method able to accurately determine these variables with little bias (0.4-1.4%) and error (small inference). Figure 14 presents the FvP profiles obtained from the two methods.

Discussion

The low bias observed between the methods and moderate to almost perfect correlations would suggest that the relationships generated are (expectedly) closely related, however the range in confidence intervals and typical error scores highlight not all variables are well predicted from a single sprint. Note that the multiple sprint method is referred to as the 'criterion' measure, it is possible that the mechanical variables determined from a single trial better represent actual sprinting ability. However, because the multiple trial variables account
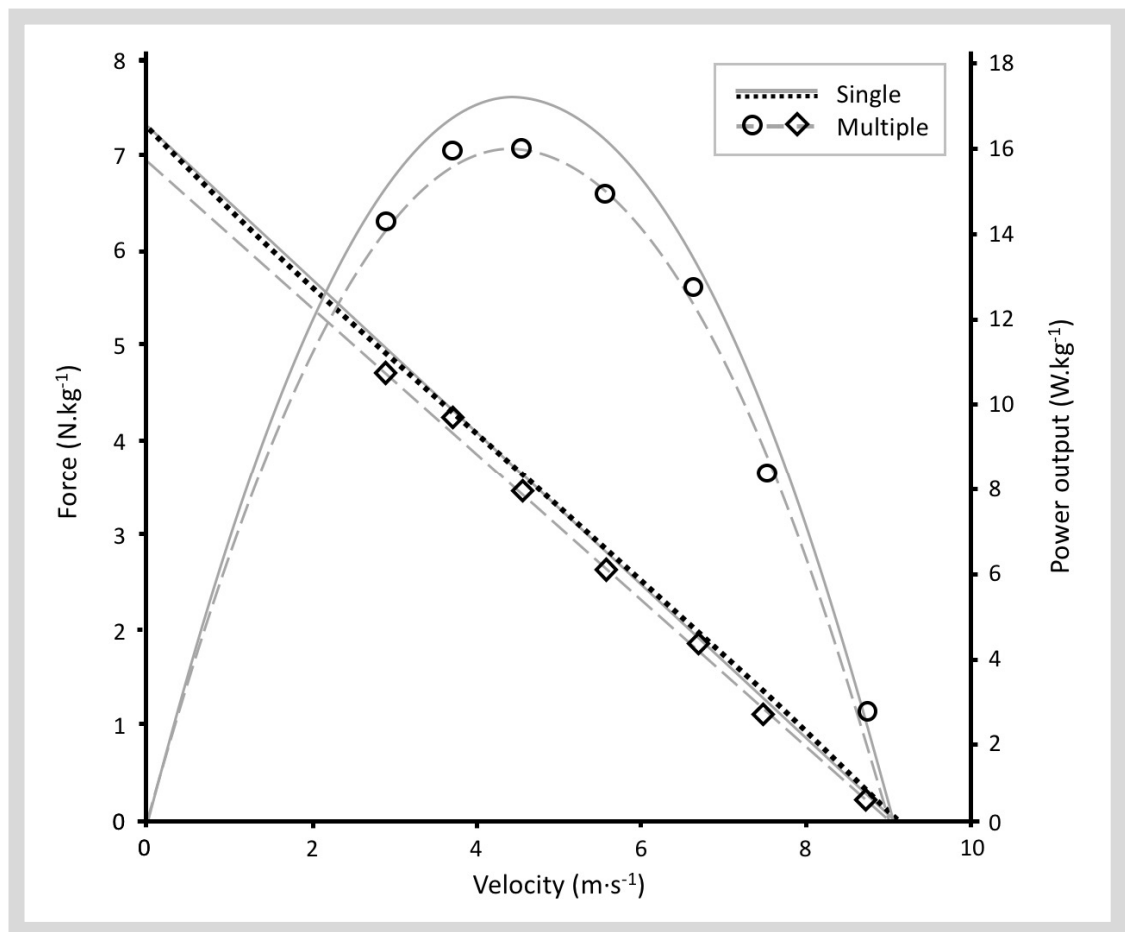
Figure 14. Graphical representation of the comparisons between multiple and single trial force-velocity-power methods.
Solid grey lines represent the single sprint method, where dashed grey lines represent the multiple sprint method. The data points represent individual sled trials (related to the multiple trial method).

for the methodological specificities of sled sprinting for practical application to training, the discussion that follows is concerned with the ability of the single sprint method to accurately predict the multiple sprint variables.

Overall, power capacity was similar between methods, albeit greater in the single trial method (6.4-7.3% bias), with moderate error scores for both absolute and relative power. The ability to generate velocity at low levels of force (v_0) were very highly related, with small levels of typical error in prediction ability. Force at low velocities was less correlated (although still with large to very-large interpretations) with increased levels of error. These findings may be a result of the increased muscular effort required to accelerate greater mass (i.e. the inertia), which is not considered in the in the multiple-trial method, incrementally impeding $v_{h_{max}}$ ability (Lakomy, 1985). In other words, as resistance is increased, greater work is performed

Table 9. Comparison of mechanical relationships & optimal loading variables between single & multiple sprint methods

Mechanical Variables	Multiple sprint		Single sprint		Comparison of methods (N=27)		
	M	±SD	M	±SD	Absolute bias (90% CIs)	Pearson's (r)	Typical error Interpretation (ES)
Force-velocity-power relationship							
v_0 (m·s^{-1})	9.13	±0.80	9.27	±0.86	0.14 (0.09; 0.18)	0.99	Small (0.13)
F_0 (N)	562	±76	589	±81	26.65 (6.64; 46.65)	0.71	Large (0.71)
Rel F_0 (N·kg^{-1})	6.97	±0.70	7.37	±0.84	0.40 (0.16; 0.64)	0.86	Moderate (0.53)
S_{Fv}	-61.8	±9.34	-63.8	±8.41	1.96 (-0.23; 4.16)	0.73	Large (0.70)
P_{max} (W)	1286	±219	1370	±260	84.75 (37.14; 132.37)	0.84	Moderate (0.55)
Rel P_{max} (W·kg^{-1})	16.0	±2.53	17.2	±3.14	1.20 (0.63; 1.78)	0.83	Moderate (0.57)
Optimal loading characteristics							
F_{opt} (N)	281	±38	294	±40	13.51 (3.58; 23.45)	0.72	Large (0.71)
Rel F_{opt} (N.kg^{-1})	3.51	±0.34	3.68	±0.42	0.18 (0.05; 0.30)	0.50	Large (0.88)
v_{opt} (m.s^{-1})	4.58	±0.40	4.60	±0.43	0.02 (0.00; 0.04)	0.99	Small (0.12)
L_{opt} (kg)	64	±8.9	67	±9.2	3.10 (0.78; 5.42)	0.70	Large (0.73)

Values are means ±SD, absolute bias (in respective units) with 90% confidence intervals (CI), Pearson's correlation coefficient, and typical error estimate in standardized effect (ES).

v_0 = theoretical maximum velocity; F_0 = theoretical maximum force; Rel = relative to body mass; S_{Fv} = slope of the linear force-velocity relationship; P_{max} = peak power production determined from the apex of the power-velocity relationship; 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} = meters per second; N = Newton; W = Watt; kg = kilogramme.

to accelerate up until $v_{h_{max}}$, resulting in progressively larger disparities between methods closer to the *y*-axis. The influence of fatigue, both within sprint bouts (i.e. after ~5 s of maximal effort) or accumulated between and between sprint trials, may partially explain the results observed. Furthermore, the influence of movement technique becoming progressively dissimilar as external mass is added to the system may have contributed to differences in mechanical ability with greater loads.

While still exhibiting moderate to large correlations, F_{opt} prediction presented large error scores. Furthermore, backwards translation from F_{opt} and v_{opt} showed the single trial method over-estimated multiple-trial L_{opt} by 3.1 kg (5.0±3.7%) on average. While this still may still provide some useful information, the associated error likely constitutes a worthwhile difference in long term adaptations. Contrastingly, the prediction ability of v_{opt} was the highest out of all the variables tested. With an almost perfect correlation, a raw mean difference of 0.02 m.s^{-1}, and an almost trivial typical error score (ES=0.12), there is high agreement between methods for the assessment of v_{opt}. Proving somewhat of a circular limitation, the problem is consequently the translation of v_{opt} into a useable training resistance, requiring assessment of the magnitude of stimulus presenting said velocity decrement. As explored in Chapter 3, while v_{opt} is maintained across multiple surfaces (accepting minor variation in v_0), L_{opt} can change drastically based on friction conditions and equipment (e.g. different sled). This means that even if loading protocols are tested and associated with a particular v_{opt}, this will not remain constant with either surface, or changes in athlete ability.

To determine the optimal sled loading conditions with reasonable accuracy a multiple sprint method should be used. It may be possible, however, to profile a simple *load*-velocity relationship, and then overlay the v_{opt} determined from the single sprint method to calculate a simple, friction inclusive L_{opt} value. Further, a multiple sprint method performed with less loading protocols (2-4, including an unloaded sprint) might allow accurate assessment of mechanical variables in familiarized athletes. We would suggest monitoring equation fit within testing (similarly to the operating procedures in Chapter 4, and displayed in Appendix 7), which should mitigate some of the risk of inaccuracies, and allow the practitioner to assess whether additional trials are required.

Practical applications

- While the Fv characteristics from both methods were similar, large error was associated with predicting sled-training F_{opt} and L_{opt} from a single sprint. Consequently, L_{opt} can be approximated to ~3 kg (on average), however its calculation requires knowledge of the friction coefficient characteristics of the testing and training surface.

- v_{opt} was very similar between methods with negligible error associated, suggesting a possible route for determining optimal sled resistance from a single sprint. Furthermore, this may have application to other resisted sprint modalities where resistance can be programmed based on velocity decrements (e.g. isokinetic sprint drums).

- Practitioners may consider combining the two techniques by using a multiple trial method to comprise a simple load-velocity relationship, and fit this relationship with the v_{opt} determined from the single sprint method. The unloaded sprint should feature as a data point, with potentially fewer loading conditions to reduce assessment time.

CHAPTER 6

DISCUSSION, PRACTICAL APPLICATIONS AND CONCLUSIONS

Preface

Given each experimental chapter features individual discussion and practical application sections, this chapter functions as a shortened synthesis of the main findings from the thesis in context with the current literature, with emphasis on the global practical applications. The overarching goal of this section is to enhance the current understanding of loading determination during resisted sprinting, force-velocity-power and optimal load profiling techniques, and the bandwidth in which these profiled variables exist in recreational and sprint trained athletes.

Discussion

With the succession of all aims, this thesis provides novel theories and data in the realm of power profiling and resisted sprinting. Namely, this thesis 1) quantified friction characteristics and kinetics during sled towing, and provided a theoretical basis for application of these theories to sled sprinting; 2) determined whether force-velocity-power (FvP) relationships could be accurately profiled using a multiple-trial method during over-ground sled-resisted sprinting; 3) quantified the optimal sled loading conditions for maximizing power production; 4) compared mechanical variables and optimal loading conditions between recreational and highly trained sprint athletes; and 5) demonstrated that optimal loading could not be accurately profiled from a single sprint.

Power-profiling is a rapidly developing area in sport science practice, with researchers endeavouring to assess these mechanical characteristics in increasingly practical and specific ways (Morin & Samozino, 2016; Samozino et al., 2016). A review of the FvP profiling literature revealed significant investigation into jumping or cycling, using either multiple trial or single trial methods to determine mechanical characteristics. While a number of studies have been recently released (Cross et al., 2015; Mendiguchia et al., 2016; Nagahara et al., 2016; Rabita et al., 2015; Samozino et al., 2016), research examining mechanical profiling

during sprint running was somewhat limited. The studies that exist either used multiple (Jaskólska et al., 1998) or single trials (Morin et al., 2010) during treadmill sprinting, or unloaded sprints overground (Rabita et al., 2015; Samozino et al., 2016) to characterize power expression. While optimal loading characteristics have been widely investigated in single extension movements and sprint cycling (Kawamori & Haff, 2004; Soriano et al., 2015), only three studies have examined optimal loading characteristics across multiple sprints on treadmill ergometers (Andre, Fry, & Lane, 2013; Jaskólska et al., 1999; Jaskólski et al., 1996). Importantly, none calculated the exact conditions for maximal power from FvP relationships. Furthermore, given very few athletes have access to these machines, the applicability of their findings to training is limited. These factors strengthen the rationale for further investigation into the assessment of these characteristics during overground sprinting. Practically, in order to characterize power, while simultaneously quantifying the conditions for optimal loading, it was deemed essential to use multiple trials of resisted sprints. For the purposes of the thesis, resisted sprint sleds were chosen due to their prevalence in both literature and practice (Petrakos et al., 2016), and hence accessibility for those wishing to replicate these methods. The first step in profiling FvP relationships required understanding the determinants of quantifying resisted sprint kinetics.

Quantifying kinetics during resisted sled sprinting requires the assessment of loading directly experienced by the athlete. Unlike the commonly profiled vertical jumping, the effective loading on an athlete performing a resisted sprint is largely horizontal, and is therefore determined not only by the normal loading applied to the sled, but the interaction between the sled and surface it is being dragged across (i.e. friction characteristics). Despite its prevalence, sled resistance conditions have either been quantified as normal loading or velocity decrements (Petrakos et al., 2016; Rumpf et al., 2015); neither of which allow for the accurate assessment of kinetics during a sprint effort. Only two studies explicitly explored the concepts of friction force with relation to sled sprinting, with both suffering from methodological limitations or practical applicability (Andre, Fry, Bradford, et al., 2013; Linthorne & Cooper, 2013). As such, the first aim and experimental study in this thesis functioned to quantify the friction characteristics of sled towing, for application to sled sprinting. A winch device was used to pull a common sprint sled equipped with a high sample rate load cell across a specialized track surface in order to determine the stability of friction

coefficients (μ_k) under variable sled mass with constant velocities, and with constant sled mass and varying velocity. All variables associated with the experiment were determined as reliable (ICC>0.99, CV<4.3%). Similar to previous research (Blau, 2008; Linthorne & Cooper, 2013) a linear relationship (R^2=0.994-0.995; P<0.001) was observed between friction force and normal force, suggestion no change in μ_k with loading. With changing velocity, however, roaming μ_k values were observed which were well predicted via a quadratic equation (R^2=0.999; P<0.001). Although the previous sport science research suggested that it was not a factor (Andre, Fry, Bradford, et al., 2013; Linthorne & Cooper, 2013), this result was relatively common in engineering literature (Braun & Peyrard, 2011). The 'stick-slip' mechanism, as an artefact of the interaction between the sled and the rubberised testing surface, likely explains the results observed (Berman et al., 1996). To summarise, the experiment revealed stable friction coefficients with changing sled mass, but dependence on towing velocity. Practically, if the aim is to quantify pulling forces, μ_k and associated effective loading should be calculated from instantaneous velocity on athletics tracks. Without considering these factors, large magnitudes of error can be introduced, and associated loading on the athlete can be misrepresented. A number of equations were determined and provided for application to sled resisted sprinting, including accounting for pulling angle from changing tether lengths.

Having determined a theoretical basis for assessing sled sprint kinetics, the second experimental study sought to integrate these methods to quantify FvP metrics and optimal loading conditions for maximizing horizontal power (aims 2-4). Sprinters and recreational level athletes performed multiple trials of sled resisted sprints, from which force and power were calculated at maximum velocity and plotted against each other to generate composite force-velocity and power-velocity relationships. The results from this analysis showed that, similar to previous studies (Jaskólska et al., 1998; Vandewalle, Peres, Heller, et al., 1987), the method allowed force-velocity and power-velocity relationships to be accurately (R^2=0.997 and 0.977, respectively; P<0.001) and reliably profiled (effect size [ES]=0.05-0.50; ICC=0.73-0.97; CV=1.0-5.4%). Accordingly, optimal conditions for maximizing peak power were quantified, and represented much greater resistance than currently recommended and used in the resisted sprint literature (Petrakos et al., 2016). Specifically, optimal normal loading was 78±6 and 82±8% of body-mass (dependent on μ_k), representing a resistance of

279±46 and 283±32 N at 4.19±0.19 and 4.90±0.18 m·s⁻¹, for recreational athletes and sprinters respectively. The greatest magnitude of loading found in the literature was approximately 46% of BM (Kawamori et al.), with most studies using between ~7-12% of BM on varying surfaces (7.5-15% velocity decrement) (Petrakos et al., 2016), which serves to contrast the results from this study. Given the prevalence of horizontal power to sprinting performance (Morin et al., 2012; Rabita et al., 2015), evidence strongly suggests practitioners and researchers should re-evaluate the current paradigm of selecting magnitude of sled resistance based on minimization of kinematic alterations (Alcaraz et al., 2009; Lockie et al., 2003).

The mechanical profiling method using sleds provided accurate results for recreational and sprint trained individuals alike. Compared to recreational athletes, sprinters displayed greater absolute and relative maximal power (17.2-26.5%; ES=0.97-2.13; *P*<0.02), reminiscent of much greater velocity production (maximum theoretical velocity, 16.8%; ES=3.66; *P*<0.001; *most likely*). Jaskólska et al. (1998) reported similar results, where velocity dominant athletes were faster at lesser resistance conditions. Optimal force and normal-load did not clearly differentiate between groups (unclear and *likely* small differences; *P*>0.05), and sprinters developed maximal power at a much greater levels of velocity (16.9%; ES=3.73; *P*<0.001; *most likely*). These results align with recent literature (Morin et al., 2010; Morin et al., 2015; Rabita et al., 2015) suggesting an ability to generate force at greater velocities characterizes well-trained sprinters.

The second experimental study clearly provided a 'proof-of-concept' for the ability to generate FvP relationships and determine optimal loading conditions for resisted sleds. Given recent investigation has validated a method of determining mechanical characteristics during a single unloaded sprint (Samozino et al., 2016), assessing the ability of this method to quantify optimal sled loading conditions was seen as a valuable addition to the thesis, and the body of literature as a whole. To this end, study 3 (Chapter 5) tested whether these conditions could be calculated from a single sprint, by comparing mechanical characteristics calculated from a macroscopic method applied to an unloaded trial, to those from the multiple trial method developed in the previous chapter. Power and maximal force criterions showed strong correlations between methods (*r*=0.71-0.86), although the standardized typical error (TEE) similarly ranged from moderate to large (TEE=0.53-0.71). Similar trends

were observed in relative and absolute optimal force (r=0.50-0.72; TEE=0.71-0.88), with estimated optimal normal loading relatively incomparable (bias=0.78-5.42 kg; r=0.70; TEE=0.73). These results were considered to be attributed to the multiple trial method not accounting for the force necessary to accelerate the sled mass in each trial (Lakomy, 1985). However maximal velocity, and associated optimal velocity, were very well matched between the methods (r=0.99), with little bias (0.4-1.4% or 0.00-0.04 m.s^{-1}; TEE=0.12). While the FvP characteristics from both methods were undoubtedly similar, large error was observed in determining optimal force and normal loading from a single sprint. Optimal velocity was very similar between methods, suggesting practitioners could feasibly use a single sprint to accurately determine the velocity for maximizing power in sled sprinting.

Thesis limitations and delimitations

This thesis features methodological constraints, outlined below, that are important to consider when interpreting the results. Rationale and justification is included where necessary.

1. The velocities used to determine the friction coefficients implemented in Chapter 4, while much closer to those performed during sprinting than similar studies, underrepresent the values reached during sled sprinting in lighter protocols (i.e. loads promoting a ~30% velocity decrement or less). While inaccuracies may be present at these lighter loading protocols, it should be noted that practically the magnitude of error is expected to be minor, as a result of the loading magnitude itself. Moreover, an extremely well fitted regression equation was used on the data, which would suggest a sufficient estimation for the remainder of the friction-velocity relationship. Unfortunately, this could not be mitigated as it was a product of the mechanical limits of the testing equipment itself.
2. The friction assessment protocol, and thus optimal loading values, were mechanically dependent on the conditions in which they were assessed. That is, the magnitude of normal loading presented as 'optimal' in Study 4 is specific to the friction conditions of the track and sled equipment used. As such, all testing was performed indoors, on the same length of track surface in order to standardize testing conditions and friction of the

testing surface. This is acknowledged throughout the respective chapters, and for this reason optimal velocity and force are presented for direct comparison with later studies. It should be noted that this is a limitation of all profiling methods featuring resistance determined via friction, rather than specific to this thesis alone.

3. It was decided that athletes should wear their personal training gear (that is, the footwear they would use for a sprint effort), so as to better replicate maximal performance in all sporting codes tested. Consequently, sprint athletes wore different footwear to the recreational subjects (sprinting spikes vs. trainers), and while we believe the performance to be comparable, there might have been bias introduced through the use of different footwear (albeit the degree of which unclear).

4. The decision to apply sled loads in an incremental order was necessitated by the study design, and based on the operational procedures of previous research (Dorel et al., 2010; Hautier et al., 1996; Jaskólska et al., 1998, 1999; Samozino et al., 2008; Vandewalle, Peres, Heller, et al., 1987). Furthermore, it was determined during piloting that even following familiarisation athletes found cueing difficult when unable to judge the magnitude of load increase or decrease from a previous sprint. As a result, it is possible that the effects of potentiation or fatigue may have contributed to the results seen in later loading protocols.

5. Measurement of attachment height of the sled tether occurred during standing, which represents an approximation due to the roving nature of angle of pull throughout a sprint. Estimation of this variable was seen as unavoidable due to the complexity involved in its accurate measurement (e.g. 2D motion capture, or sled mounted goniometers, synced to velocity-time data). However, based on our modelling we project the effect of this inaccuracy to present minimal practical effect on kinetic output and the results observed (see Chapter 3).

Conclusions

This thesis succeeded its aims, and proved the ability to accurately determine FvP relationships and conditions for optimal loading using common sled training equipment. The value in such an approach is the determination of an easily set loading protocol that should allow more targeted and individualized prescription. Notably, the optimal conditions

for maximizing power represent much greater resistance than current guidelines, and exist within a wide range among sprinters and recreational athletes. Implementation of these methods in practice exemplifies a progressive means of quantifying individualized resistance for horizontal power training, which may reflect greater increases in applied performance measures than those currently used and recommended in practice.

Practical applications and future research

- It is imperative that researchers and practitioners consider the effects of friction during sled-resisted sprinting, acknowledging the loading experienced by the athlete is largely reliant on the characteristics of the testing surface, not only by the mass of the sled. Our results suggest μ_k is velocity dependent on athletics track surfaces, and should therefore be considered when quantifying resisted sprint kinetics. Sole reporting of normal loading should be avoided in research, to facilitate comparison of results between studies. Further, quantifying μ_k on other surfaces, using similar experiments to those featured in this thesis (higher velocity testing, and common training equipment), will help determine whether the phenomenon of velocity dependence is restricted to rubberised athletics track alone, and provide normative data for future studies and practitioners.

- The conditions for optimal loading are much greater than currently used in the literature (L_{opt} of 78-82% [for given friction conditions] vs. <46% of BM, and v_{opt} of 48-50% vs. <30% decrement of $v_{h_{max}}$), highlighting practitioners and researchers should reconsider the guidelines on which sled sprints and similar resisted sprint modalities are implemented. Future studies should look to use these methods in training studies to assess the longitudinal effects of training in optimal loading conditions on horizontal power and sprinting performance. Further, while this thesis suggests greater benefits in horizontal power and sprint acceleration performance are expected from training at optimal loading, further research and testing is necessary to determine whether this leads to worthwhile and timely adaptations in various athlete subsets (i.e. development vs. high-level; rugby players vs. sprinters).

- The wide range of optimal loading characteristics observed (69-96% BM for the given friction conditions) indicates the need for individualized training zones among both

recreational and highly-trained sprint athletes. Further research should look to test this hypothesis, and to quantify optimal loading characteristics for other homogenous and non-homogenous athlete groups (e.g. high-level rugby players).

- L_{opt} can be determined from a single sprint with moderate-large error, although its calculation is dependent on knowledge of the friction characteristics of the surface being tested. v_{opt} for resisted sprinting can be determined from a single sprint with minor error. This may have application to other resisted sprint modalities where resistance can be programmed based on velocity decrements (e.g. isokinetic sprint drums). Practitioners might consider combining the two techniques by using a multiple trial method to comprise a simple load-velocity relationship, subsequently fitting this relationship with the v_{opt} determined from the single sprint method. In this case, the unloaded sprint should feature as a data point, with potentially fewer loading conditions to reduce assessment time. This process would allow researchers and practitioners without access to the equipment necessary to assess friction characteristics the ability to determine optimal loading for testing and training conditions.

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APPENDICES

Appendix 1. Ethics approval and amendment form

A U T E C

S E C R E T A R I A T

13 April 2015

Matt Brughelli
Faculty of Health and Environmental Sciences

Dear Matt

Re Ethics Application: **15/61 Determining optimal load for maximal power during resisted sprint running.**

Thank you for providing evidence as requested, which satisfies the points raised by the Auckland University of Technology Ethics Committee (AUTEC).

Your ethics application has been approved for three years until 13 April 2018.

As part of the ethics approval process, you are required to submit the following to AUTEC:

- A brief annual progress report using form EA2, which is available online through http://www.aut.ac.nz/researchethics. When necessary this form may also be used to request an extension of the approval at least one month prior to its expiry on 13 April 2018;

- A brief report on the status of the project using form EA3, which is available online through http://www.aut.ac.nz/researchethics. This report is to be submitted either when the approval expires on 13 April 2018 or on completion of the project.

It is a condition of approval that AUTEC is notified of any adverse events or if the research does not commence. AUTEC approval needs to be sought for any alteration to the research, including any alteration of or addition to any documents that are provided to participants. You are responsible for ensuring that research undertaken under this approval occurs within the parameters outlined in the approved application.

AUTEC grants ethical approval only. If you require management approval from an institution or organisation for your research, then you will need to obtain this.

To enable us to provide you with efficient service, please use the application number and study title in all correspondence with us. If you have any enquiries about this application, or anything else, please do contact us at ethics@aut.ac.nz.

All the very best with your research,

Kate O'Connor
Executive Secretary
Auckland University of Technology Ethics Committee

Cc: Matthew Cross mcross@aut.ac.nz

A u c k l a n d   U n i v e r s i t y   o f   T e c h n o l o g y   E t h i c s   C o m m i t t e e

W A 5 0 5 F   L e v e l   5   W A   B u i l d i n g   C i t y   C a m p u s

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AUTEC Secretariat

Auckland University of Technology
D-88, WU406 Level 4 WU Building City Campus
T: +64 9 921 9999 ext. 8316
E: ethics@aut.ac.nz
www.aut.ac.nz/researchethics

20 October 2015

Matt Brughelli
Faculty of Health and Environmental Sciences

Dear Matt

Re: Ethics Application: **15/61 Determining optimal load for maximal power during resisted sprint running.**

Thank you for your request for approval of amendments to your ethics application.

I have approved minor amendments to your ethics application allowing changes to the inclusion criteria and data collection protocols.

I remind you that as part of the ethics approval process, you are required to submit the following to the Auckland University of Technology Ethics Committee (AUTEC):

- A brief annual progress report using form EA2, which is available online through http://www.aut.ac.nz/researchethics. When necessary this form may also be used to request an extension of the approval at least one month prior to its expiry on 13 April 2018;

- A brief report on the status of the project using form EA3, which is available online through http://www.aut.ac.nz/researchethics. This report is to be submitted either when the approval expires on 13 April 2018 or on completion of the project.

It is a condition of approval that AUTEC is notified of any adverse events or if the research does not commence. AUTEC approval needs to be sought for any alteration to the research, including any alteration of or addition to any documents that are provided to participants. You are responsible for ensuring that research undertaken under this approval occurs within the parameters outlined in the approved application.

AUTEC grants ethical approval only. If you require management approval from an institution or organisation for your research, then you will need to obtain this.

To enable us to provide you with efficient service, please use the application number and study title in all correspondence with us. If you have any enquiries about this application, or anything else, please do contact us at ethics@aut.ac.nz.

All the very best with your research,

Kate O'Connor
Executive Secretary
Auckland University of Technology Ethics Committee

Cc: Matthew Cross

Participant Information Sheet

AUT
UNIVERSITY
TE WĀNANGA ARONUI O TAMAKI MAKAU RAU

Date Information Sheet Produced:

__ / __ / ____

Project Title

Determining optimal load for maximal power during resisted sprint running

An Invitation

Hi, my name is **Matthew Cross** - I am a Masters student at AUT University. On behalf of my supervisors Dr. Matt Brughelli and Professor Jean-Benoît Morin, I would like to personally invite you to participate in our project that aims to determine the optimal loading for power during over-ground resisted sprinting.

It is entirely your choice as to whether you participate in the project or not. If you decide you no longer want to participate you are free to withdraw yourself or any information that you have provided for this project at any time prior to completion of data collection, without being disadvantaged in any way. Your consent to participate in this research will be indicated by your signing and dating the consent form. Signing the consent form indicates that you have read and understood this information sheet, freely given your consent to participate, and that there has been no coercion or inducement to participate by the researchers from AUT.

What is the purpose of this research?

Power-velocity and force-velocity relationships can be measured during sprint running. These relationships offer understanding of athletic capabilities, and can provide valuable guidance for individualized training prescription based on the speed or load at which athlete produces maximum power. While literature has examined profiling these relationships during constrained non-specific movements, there has been no investigation into the validity of profiling optimal loading during over-ground sprinting. This research aims to determine whether mechanical relationships and optimal load can be reliably profiled using a sled-resisted multiple sprint method over-ground, and whether optimal load can be determined using a single sprint non-resisted approach.

How was I identified and why am I being invited to participate in this research?

You are eligible to participate in 'competitive' section of this study if you are (1) between the ages of 17 and 35 years; (2) have >2 years of specific sprint training (>1 year resisted sprinting); (3) are free from disorder, or acute/chronic injury at the time of testing occasion (>3 months injury free), and (4) satisfy the minimum requirements performance (>750 IAAF points).

Alternatively, if you are a recreationally active male you are eligible to participate in the reliability section of this study – provided you meet the following criteria: (1) a male between the ages of 18 and 35 years; (2) are recreationally active (on average >2-days of physical activity per week, for >2 years); and (3) are free from disorder, or acute/chronic injury at the time of testing occasion (>3 months injury free).

What will happen in this research?

Once you have decided to participate in the study you will be asked to complete a 2 hour testing session either at the AUT-Millennium track or another track of your preference (based on suitability of track surface), and repeat identical study procedures 7 days following the initial testing occasion (if able). The study procedures are as follows:

Initially height and body weight will be measured. Following this, a complete verbal explanation of the testing procedures and equipment will occur, followed by a full body dynamic warm-up for 10-15 minutes. The warm up will be completed by submaximal 'stride-outs' of sprints performed within the marked lanes of the assessment area. The testing procedures will consist of maximal sprints performed under a selection of resisted sled loads. Specifically, you will perform a single trial of 20-45 meter sprints while towing a selection of (at most) 7 loads (unloaded, 20%, 40%, 60%, 80%, 100% and 120% of body-mass loaded sleds) interspersed with 5 minute passive rest periods. It is possible that collection may occur with multiple test subjects in one instance, cycling trials between athletes to maximize time efficiency

If you wish to continue your participation, you will be invited to return to our testing facilities for a second testing session seven days later at the same time of day. This session will follow the same procedures as the first testing session to determine the reliability and validity of the test variables.

What are the discomforts and risks?

You will be asked to perform some sub-maximal (moderate intensity) and maximal (very heavy intensity) exercise during the data collection and therefore during the latter could potentially experience discomfort for a short period of time towards the concluding moments of these maximal assessments. The intensity of the exercise will be similar to what is experienced in typical training and competition situations.

How will these discomforts and risks be alleviated?

Being an experienced athlete who regularly competes and is familiar with training at very high intensities, the exercise trials will be similar to what you have experienced within a typical weeks training and competition. If excessive discomfort is felt at any stage during the testing you are encouraged to inform the researcher with you at the time in order that they can best address the problem. If you have any questions regarding and risk or comfort that you anticipate, please feel free to address these concerns to the researcher so that you feel comfortable at all times throughout the process.

What are the benefits?

Each participant will receive a personalised comprehensive athletic assessment regarding their sprinting performance. This will include inidivualised force-velocity profiles, split times, and an approximate training load for maximal power. This information can be used to provide further insight into your personalized training recommendations. The researchers will benefit also, given that this is a novel, applied research study, and new knowledge will be gained into the ability to profile optimal load for development of peak power in sprint athletes. The results from this study will eludicate whether optimal load can effectively be determined over ground, and the findings may have strong implications regarding exercise prescription for athletes in New Zealand.

The results of this research are intended for publication, will contribute to part of my masters thesis and will also be submitted to peer-reviewed journals for publication.

What compensation is available for injury or negligence?

In the unlikely event of a physical injury as a result of your participation in this study, rehabilitation and compensation for injury by accident may be available from the Accident Compensation Corporation, providing the incident details satisfy the requirements of the law and the Corporation's regulations.

How will my privacy be protected?

Testing procedures and subsequent data collection may occur in small groups, therefore confidentiality during this period will be limited between those performing sprinting within the same session. No results will be imparted during the testing occasion, however, therefore your individual data will be protected and anonymous from other participants in your testing group. Outside of the testing occasion, your privacy will be protected by data being de-identified (an athlete code instead of name; e.g. 100m_A1), and the researcher will not disclose anyone's participation in this study. All participant data will be averaged and represented as group means. No names or pictures will be used in reporting (unless the participant gives explicit additional written consent for media purposes following AUT protocols and organised via the AUT university relations team). During the project, only the applicant and named investigators will have access to the data collected. The results of the study may be used for further analysis and submission to peer-reviewed journals or submitted at conferences. To maintain confidentiality, in all publications resulting from this research participants' data will be averaged and represented as group means.

All data will be stored on password protected computers or in locked files. Following completion of data analysis your data will be stored by the AUT University SPRINZ research officer in the AUT University SPRINZ secure Ethics and Data facility at AUT Millennium campus. Given the progressive nature of research in this field, data will be kept indefinitely for the purposes of reanalysis (should future analysis methods arise) for purposes similar to that collected; however (as per above) all forms of data will be de-identified and kept secure for the entirety of the data's storage lifetime.

What are the costs of participating in this research?

Other than your time and effort, there will be no financial cost for you being involved with this study. The first session will take approximately two hours. If you decide to participate in the second testing session, another 2 hour session will occur seven days later at the same time of day.

In the case that travel is required, a $10 petrol voucher will be supplied as koha as partial reimbursement.

What opportunity do I have to consider this invitation?

We would appreciate it if you could let us know within two weeks whether you would be available to take part in the study or not. After consideration you may withdraw your participation at any time.

How do I agree to participate in this research?

If you agree to participate please fill in the attached consent form and return to me, the primary researcher Matthew Cross.

Will I receive feedback on the results of this research?

Yes, upon completion each participant will gain a personalised athletic assessment regarding their sprinting performance, including a full mechanical profile and estimation of optimal training load for maximum power. It is your choice whether you share this information with your coach or other people.

What do I do if I have concerns about this research?

Any concerns regarding the nature of this project should be notified in the first instance to the Primary Project Supervisor: Dr. Matt Brughelli, matt.brughelli@aut.ac.nz, 09 921 9999 x7025 or ▮▮▮▮▮▮▮▮.

Concerns regarding the conduct of the research should be notified to the Executive Secretary of AUTEC Kate O'Connor, ethics@aut.ac.nz, 921 9999 ext 6038.

Whom do I contact for further information about this research?

Researcher Contact Details:

Matthew Cross, mcross@aut.ac.nz, ▮▮▮▮▮▮▮▮.

Project Supervisor Contact Details:

Dr. Matt Brughelli, Sport Performance Research Institute New Zealand (SPRINZ), School of Sport and Recreation, Faculty of Health and Environmental Sciences, AUT University, Private Bag 92006, Auckland 1020, matt.brughelli@aut.ac.nz, 09 921 9999 x7025 or ▮▮▮▮▮▮.

Approved by the Auckland University of Technology Ethics Committee on 13/04/2015, AUTEC Reference number 15/61.

Consent Form For use when laboratory or field testing is involved.	**AUT** UNIVERSITY TE WĀNANGA ARONUI O TAMAKI MAKAU RAU

Project title: Determining optimal load for maximal power during resisted sprint running

Project Supervisor: *Dr Matt Brughelli*

     Prof. Jean-Benoît Morin

Researcher: **Matthew Cross**

○   I have read and understood the information provided about this research project in the Information Sheet dated 19th Nov 2015.

○   I have had an opportunity to ask questions and to have them answered.

○   I understand that I may withdraw myself or any information that I have provided for this project at any time prior to completion of data collection, without being disadvantaged in any way.

○   I am not suffering from any current injury, illness, or disorder that may impair my ability to perform the required tasks nor am I outside the limits of the required age range of 17 to 35 years.

○   I agree to answer questions and provide physical effort to the best of my ability throughout testing.

○   I agree to take part in this research.

○   I consent to the indefinite storage of my de-identified data for re-analysis, should future similar uses arise.

○   I wish to receive a copy of the report from the research (please tick one): Yes○   No○

Participant's signature: ....

Participant's name :   ....

Participant's Contact Details (if appropriate):

………………………………………………………………………………..

………………………………………………………………………………..

………………………………………………………………………………..

Date:

Appendix 4. Minimum performance criteria for athletes (from IAAF 2014 standards)

|	100m	110mH	200m	300m	400m	400mH
Time (s)	11.48	15.9	23.34	36.95	51.89	58.43

Minimum performance criteria for each sprint event

Appendix 5. Load calculation and in-session monitoring spreadsheet (green boxes are edited either before or during testing)

| Resisted sprinting worksheet			
Athlete number	5	Sled (kgs)	5.64
Sporting code (R/S)	S	Harness (kgs)	0.34
BM (kgs)	74.8		
Stature (m)	186		
Age (y):	25		
Previous injuries	N/A		

Protocols	Loading Protocols Additional Load	Preliminary Results Peak v (m/s)
Load 0:	0.0	9.4
Load 1:	9.4	8.0
Load 2:	24.4	7.0
Load 3:	39.5	5.9
Load 4:	54.5	4.9
Load 5:	69.5	4.0
Load 6:	84.6	3.4

DO NOT EDIT			
	Velocity	Load	Prop. P
Intercept	9.4	0.0	0
Load 1:	8.0	14.9	164.24
Load 2:	7.0	30.0	249.746
Load 3:	5.9	45.0	299.0002
Load 4:	4.9	60.0	321.8222
Load 5:	4.0	75.1	322.912
Load 6:	3.4	90.1	306.2992
Intercept	0.0	133.7	0

Actual loading	Load 1	Load 2	Load 3	Load 4	Load 5	Load 6
	5.6	5.6	5.6	5.6	5.6	5.6
	5.0	22.6	22.6	22.6	22.6	22.6
	2.5	1.3	10.0	22.5	22.5	22.5
	1.3	0.5	5.0	5.0	21.8	21.8
	0.5		1.3	2.5	2.5	10.0
			0.5	1.3		5.0
				0.5		2.5
Total	14.9	30.0	45.0	60.0	75.1	90.1
Expected	15.0	30.1	45.1	60.1	75.2	90.2
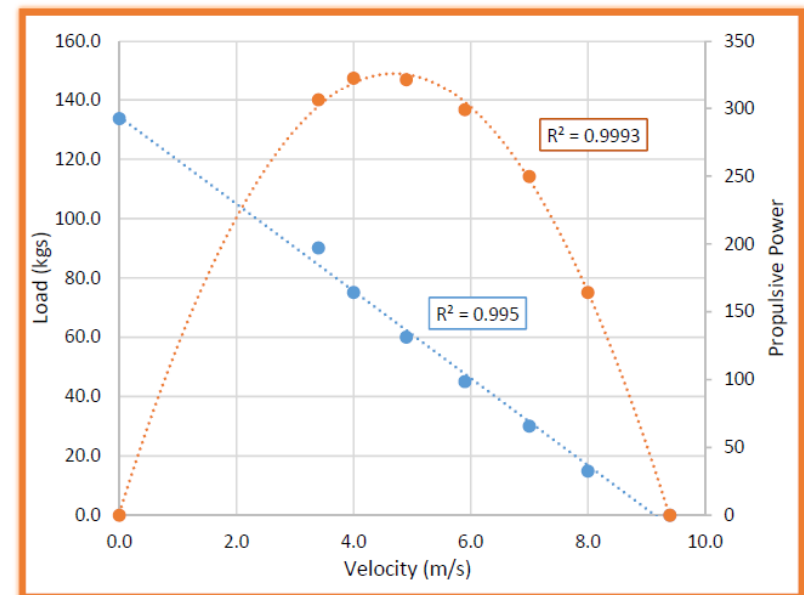
Appendix 6. Custom built LabVIEW program for application of exponential decay, and analysis of single trial data files
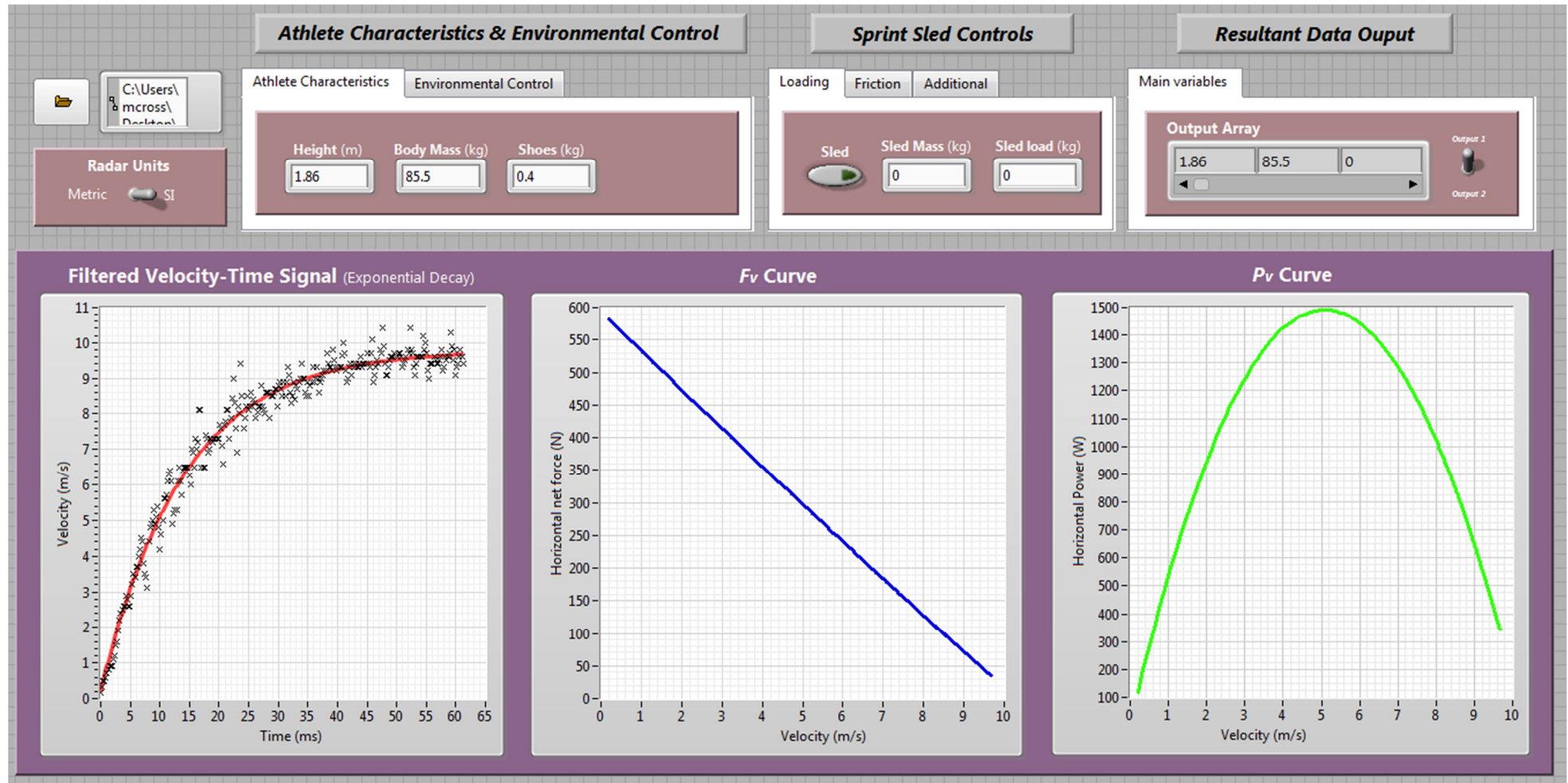
**Appendix 7.** Example analysis sheet for post-processed data

Step 1 = Power intercepts						
	F_f	F_{aero}	Totals	v_{max}	Prop	Average
Theoretical	0	0	0	9.366355	0	
UL	0.00	24.11	24.11	9.2	221.4937	623.58
Sled 20%	59.9158	17.588	77.5038	7.8	608.0661	873.616
Sled 40%	125.079	14.3402	139.4192	7.1	987.6902	1163.31
Sled 60%	192.357	10.0459	202.4029	5.9	1200.138	1227.74
Sled 80%	256.499	6.89823	263.3972	4.9	1294.194	1288.67
Sled 100%	315.878	4.72809	320.6061	4.1	1304.171	1240.35
Sled 120%	368.266	3.04641	371.3124	3.3	1212.42	1151.34
Theor. y			561.3354	0.0	0	

Propulsive Power			
	x2	x	c
Orig. Coeff	-58.26	546.86	17.332
New (diff)		-116.52	546.86
	x(max)	4.693272	
	y(max)	1300.613	

Step 2 = F-V intercepts

BM
74.82

Optimum Load of P_{max}	
$F_{f\ opt}$ (N)	280
F_{aero} @ v_{opt}	6
Load (kg)	64.278
% BM	86%

Height	Weight	F. Area	CD	μk (P_{peak})
1.86	74.82	0.53	0.29	0.466

Peak power			Mechanical					
P_{MAX}	P_{MAX} (#2)	% Bias	v_0	F_0	S_{FV}	L_0	R^2	P-value
1301	1314	**1.06%**	9.37	561.34	-59.88	190.41	0.998	0.000000

Optimal force/load Peak Power					
L_{OPT}	$L_{OPT\ (\%BM)}$	F_{OPT}	v_{OPT}	R^2	P-value
64	85.9%	280	4.7	0.990	0.000001

Force-velocity & power-velocity

$y = -58.26x^2 + 546.86x + 17.332$
$R^2 = 0.9898$

$y = -59.88x + 561.49$
$R^2 = 0.9984$
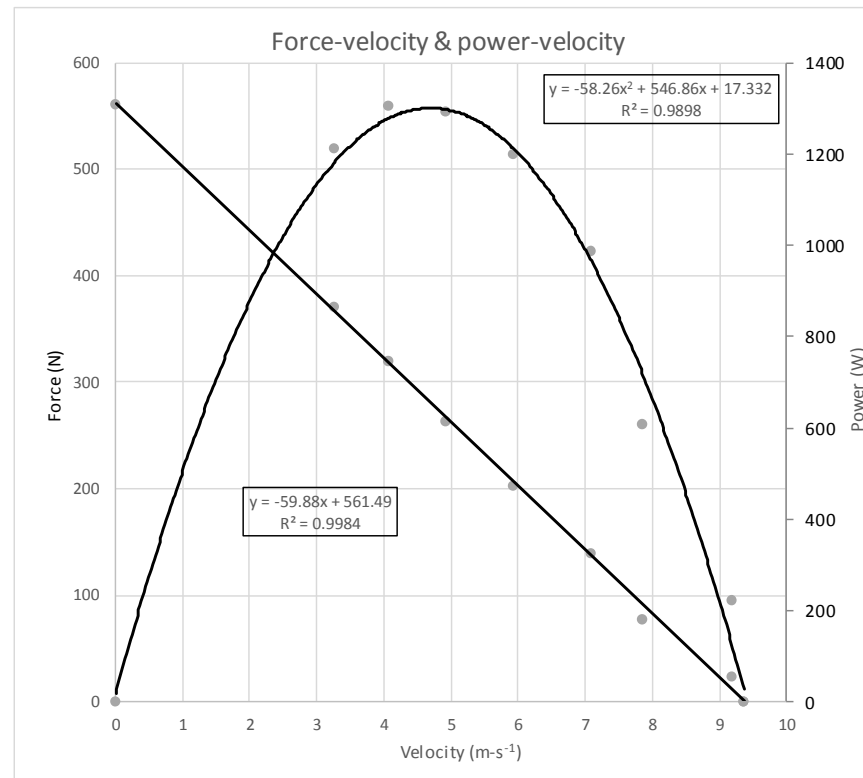
Appendix 8. Composite individual power-velocity-relationships (sprinters)

Relative horizontal force-velocity relationship

$R^2 = 0.9698$

Relative horizontal force ($N \cdot kg^{-1}$)

Velocity ($m \cdot s^{-1}$)

Relative horizontal power-velocity relationship

$R^2 = 0.9265$

Relative horizontal power ($W \cdot kg^{-1}$)
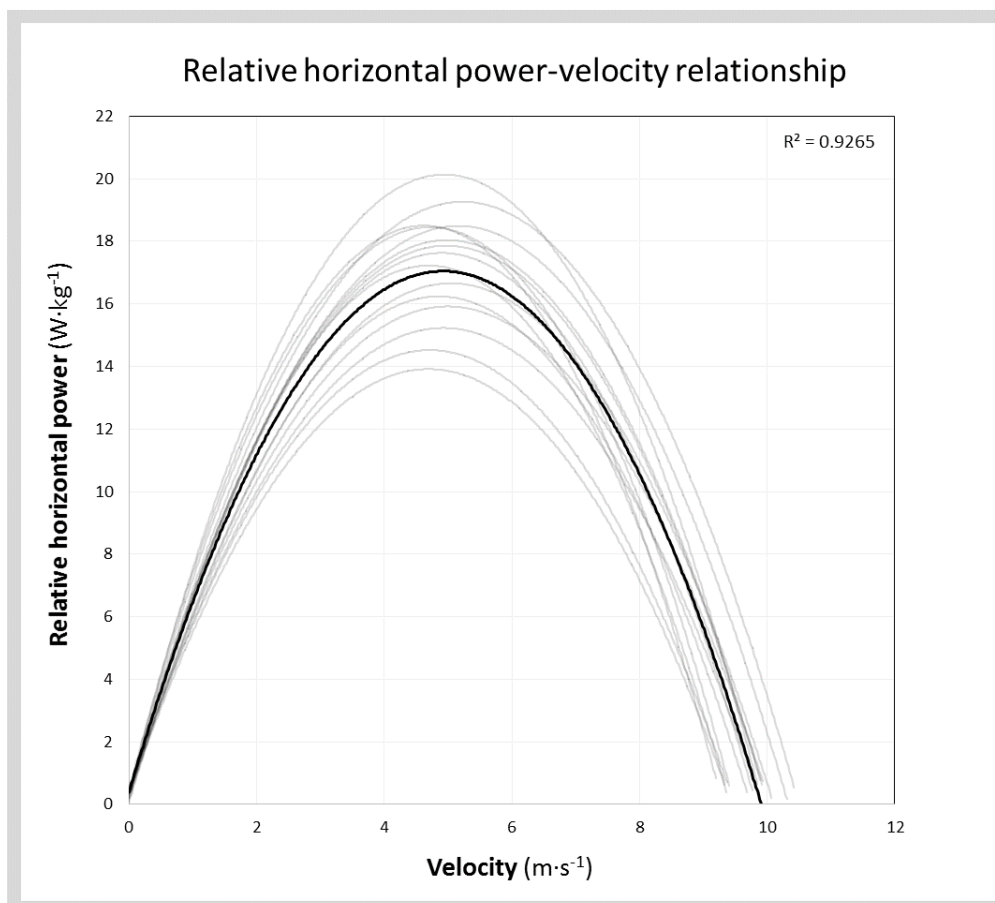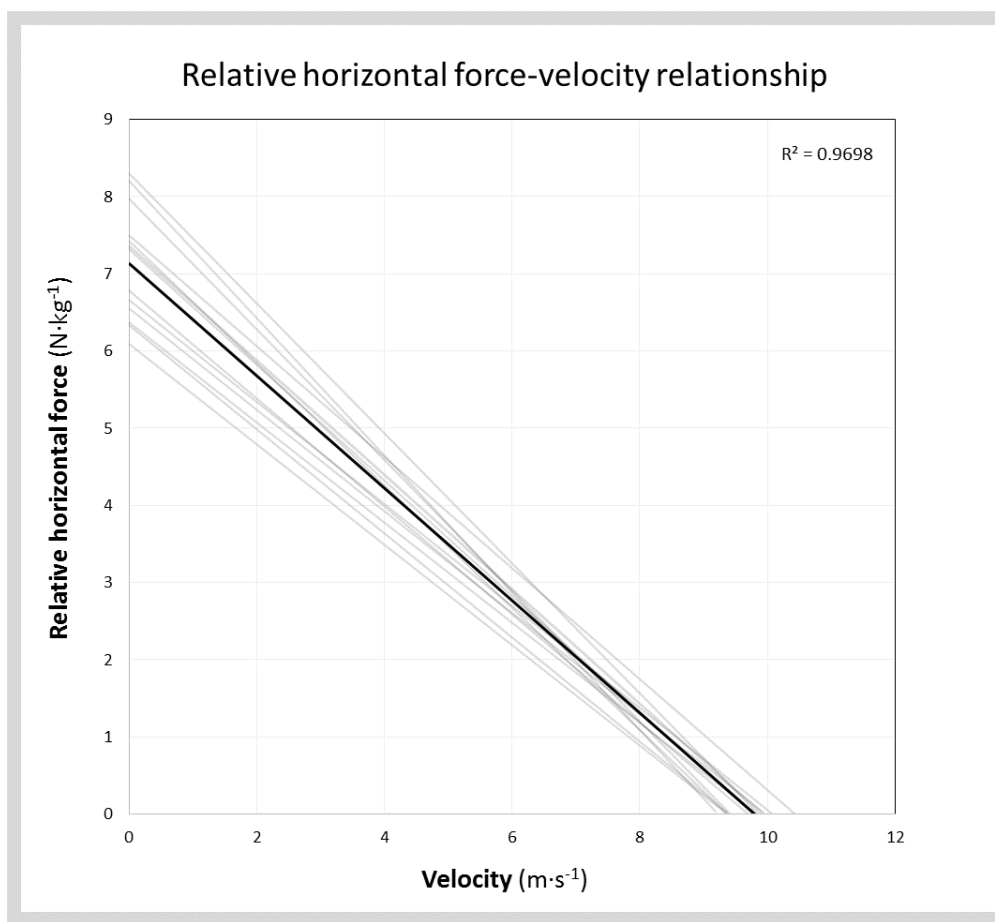
Velocity ($m \cdot s^{-1}$)

Appendix 9. Composite individual power-velocity-relationships (recreational)

Relative horizontal force-velocity relationship

$R^2 = 0.9704$

Relative horizontal force ($N \cdot kg^{-1}$)

Velocity ($m \cdot s^{-1}$)

Relative horizontal power-velocity relationship

$R^2 = 0.9094$

Relative horizontal power ($W \cdot kg^{-1}$)

Velocity ($m \cdot s^{-1}$)