THE EFFECTIVENESS OF RESISTED SPRINTING TO IMPROVE SHORT DISTANCE SPRINT PERFORMANCE IN YOUNG ATHLETES

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ABSTRACT

Speed is an important athletic quality and needs to be developed in young athletes, this may be best achieved using specific forms of sprint training. Resisted sled training is a sprint specific form of training widely used by coaches and practitioners. The two modes of resisted sled training that exist are sled pushing and pulling, with limited research available for pulling and little, if any, available for pushing in any population. The overarching question that guided this thesis was "what are the acute and chronic training responses to sled pushing and pulling in young athletes?"

The aims of the thesis were to: review existing literature related to acute and chronic training responses to resisted sled pushing and pulling; examine the reliability, linearity, and utility of individual load-velocity profiles to prescribe training loads during sled pushing and pulling in young athletes; assess the effectiveness of unresisted and resisted sled pull and sled push training on short distance sprint performance across a wide array of individualised loads; and, provide practical programming guidelines on how to integrate resisted sled training into an athlete's training.

The main findings of this thesis were: 1) across existing literature little uniformity exists with regard to prescription of load for resisted sled training although heavier loads appeared to provide a stimulus for higher horizontal force application. Loads can be applied across different zones of training such as technical competency, speed-strength, power and strength-speed. 2) Sled pushing and pulling produce a highly linear relationship ($r > 0.95$) between load and velocity. The slope of the load-velocity relationship was found to be reliable (CV = 3.1%), with the loads that cause a decrement in velocity of 25, 50 and 75% also found to be reliable (CVs = <5%). However, there was large between-participant variation (95%CI) in the load that caused a given Vdec in both sled pushing and pulling. Loads of 14-21, 36-53, 71-107 and 107-160% body mass (%BM) caused a Vdec of 10, 25, 50 and 75% in sled pulling. Loads of 23-42, 45-85 and 69-131% body mass (%BM) caused a Vdec of 25, 50 and 75% in sled pushing. 3) Both forms of resisted sprint training demonstrated a clear trend for greater and more consistent improvements in sprinting force, power and performance over short distances when training with heavier sled loads (as compared to a lighter load or unresisted sprint training).

Several practical applications may be offered from the findings. Due to the linearity and reliability of the load-velocity relationship, coaches are urged to prescribe individualised sled loads based on a target decrement in velocity rather than simply prescribing all athletes the same load as a set percentage of body mass. Both sled pushing and pulling were effective sprint specific modes of training to enhance overall sprint performance, with the latter found to be more sprint specific due to the use of the arms. Heavier loads during both forms of resisted sled training appeared to yield the greatest benefit to young athletes in short distance sprint performance, however a targeted approach to sled loading may influence different phases of the sprint.

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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 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 to 7 of this thesis represent separate papers that have either been published or have been submitted to peer-reviewed journals for consideration for publication. The contributions of myself and the various co-authors of these papers are outlined at the beginning of each chapter. All co-authors have approved the inclusion of the joint work in this doctoral thesis.

Micheál J. Cahill

PUBLICATIONS

The following publications have arisen from the research conducted in fulfilment of the degree of Doctor of Philosophy.

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The student was the main contributor of the research and subsequent analysis and interpretation of the research results in this thesis. Additionally, the student was the primary contributor to the writing of research ethics applications, progress reports and papers.

Chapter 2 – MJC - 85%, JC – 5%, JLO – 4%, KC – 2%, RSL – 2%, MC – 2%

Chapter 3– MJC - 85%, JLO – 5%, JC – 4%, KC – 2%, RSL – 2%, MC – 2%

Chapter 4– MJC - 85%, JLO – 5%, JC – 4%, KC – 2%, RSL – 2%, MC – 2%

Chapter 5– MJC - 85%, JLO – 5%, JC – 4%, KC – 2%, RSL – 2%, MC – 2%

Chapter 6 – MJC - 85%, JLO – 5%, JC – 2%, KC – 2%, RSL – 2%, MC – 2%, JEL – 2%

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We, the undersigned, hereby agree to the percentages of participation to the chapters identified above:

Supervisors

Prof. John Cronin	Prof. Jon Oliver,	Dr. Ken Clark
Primary	Secondary	Tertiary

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CHAPTER 1. PREFACE

1.1 Background

Sprinting has been shown to be a fundamental physical component necessary for success in youth team sport competition [1-3]. A failure to fully develop sprint speed during childhood may also restrict opportunities as an adult, as speed is often reported to distinguish between adults of differing competitive standards [4]. The ability to accelerate and to attain maximal velocity are both components of speed and should be considered in the development of speed during childhood. The acceleration phase of sprinting can be defined as the distance needed to attain maximal velocity [5]. The distance at which maximal velocity is achieved is specific to the athlete's characteristics. According to Mero, Komi and Gregor [6], elite sprinters can accelerate for 30-50 m in comparison to non-elite sprinters or team sport athletes who would achieve maximum velocity before 30 m [7]. However, 11-16 year-old boys have been shown to attain maximum velocity between 15 - 30 m [8].

It is clear that all aspects of speed develop through childhood and, as with other components of fitness, improvements have been reported to follow a non-linear process [9-11]. The development of speed throughout childhood will be influenced by increases in muscle cross sectional area and limb length, biological and metabolic changes, morphological alterations to the muscle and tendon, neural motor development as well as biomechanical and co-ordination factors [12]. Given the interaction of so many variables, identifying a single primary mechanism responsible for improvements in speed at different stages of growth and maturation is difficult. However, biomechanical analyses can provide useful information regarding the development of speed, which in its simplest form is a function of stride frequency and stride length. Stride frequency decreases slightly during late childhood due to small increases in ground contact time, but this is more than compensated for by greater increases in stride length throughout childhood and adolescence [10,13].

The developmental changes that underpin natural gains in speed may help to identify the types of training regimes that can be most successfully implemented at different stages of growth and development [14-16]. Training can also be considered in terms of both non-sprint specific (e.g. resistance and plyometric training) and sprint-specific training. Although, there is large volume of non-sprint specific training studies in youth athletes [15-18]. There is much less literature available on sprint specific training, however within the research that does exist it suggests that, in line with training specificity, sprint-specific training will provide greater benefits in speed/acceleration development compared to non-specific training [19]. However, more research is needed in sprint specific training in young athletes. Given the importance of short distance sprint performance in sport, coaches should assess and monitor improvements to ensure the continued development of speed in young athletes.

1.2 Development of speed in young athletes

Improvements in speed during childhood follow a non-linear process. Viru *et al*. [11] suggested the existence of a preadolescent spurt in speed between the ages of 5-9 years followed by a second adolescent spurt around the onset of sexual maturation. This developmental trend has recently been confirmed for both acceleration and speed in a large sample of Japanese boys sprinting over 50 m covered with force plates [10], with an adolescent spurt in speed for boys also confirmed by others [13,20,21]. However, whether girls experience any adolescent spurt is unclear with conflicting results in the literature

[9,22,23]. The pre-pubertal spurt has been attributed to rapid central nervous system development during the first decade of life, with the adolescent spurt primarily attributed to a rise in hormone levels with maturity [11,12]. This means sprint ability is similar in immature boys and girls but developmental rates diverge with the onset of sexual maturation; with boys increasing speed more rapidly as a result of increased testosterone levels and greater lean muscle mass gains, while girls become somewhat disadvantaged by the accumulation of more fat mass [22,24].

Biomechanical factors in the development of acceleration and maximal velocity sprinting

Understanding developmental trends in speed development are predominantly based on literature examining sprint performances of distances between 25-50 m [11], which will combine elements of both acceleration and maximal speed. Acceleration is associated with longer periods of ground contact, providing the opportunity to generate a large net impulse [25], while maximal velocity sprinting is associated with shorter periods of ground contact and a rapid rate of force development [26]. Supporting the specificity of acceleration and maximal speed, Chelly and Denis [27] reported a common variance of only 21% between these two variables in 16 year old children. The authors reported that acceleration was dependent on relative power, whereas a greater absolute power and increased leg stiffness were required for maximal speed. Therefore, different phases of sprinting represent unique characteristics which may be influenced differently by a common mode of training.

More recently, cross-sectional and longitudinal research has also confirmed the importance of leg stiffness, relative vertical stiffness and relative maximal vertical force production on the development of maximal sprint speed in boys [28,29]. Changes in leg stiffness support a role of growth and increasing leg length and contact length during sprinting, which is the distance covered while in contact with the ground. While absolute force production increases with maturation, it is relative force production that is important for sprint performance. Vertical relative force production during sprinting seems to be an innate quality remaining unchanged with advancing age and maturation [9,10,28,29]. Conversely, relative horizontal propulsive forces have been shown to increase with age in boys and girls, particularly during the acceleration phase, thus mirroring the developmental trend for improvements in stride length and speed [9,10]. Collectively, findings from various researchers suggest that as youth mature they spend slightly longer time on the ground, but growth-related changes enable them to cover more distance during the ground contact period, while high levels of stiffness and relative vertical force coupled to maturity-related increases in relative propulsive force allow more mature youth to propel themselves further during the flight phase.

1.3 Trainability of speed in young athletes

Practitioners should consider how different modes of training can influence speed development, as well as how maturation and training age can affect the training response. Sprint-specific training refers to training that involves either free sprinting or adapted forms of sprinting such as, the different forms of resisted sprinting (e.g. sled pushing, sled pulling, parachute, uphill), assisted sprinting (e.g. downhill, towed), backward running and sprinting, and technical sprint training (e.g. sprint mechanics). Non-specific training includes modes of training that do not include sprinting and instead typically involve different forms of resistance training, plyometric training and combined training methods. Non-specific training methods predominantly include movements in a vertical plane (e.g. squatting), but with scope to include horizontal movements.

Non-Sprint Specific Training

Non-specific sprint training typically includes different forms of resistance, plyometric and combined training that predominantly focus on movements in the vertical plane. The ability of these non-specific training methods to transfer to speed gains is supported by the observation that relative vertical force and stiffness are important determinants of speed. In a meta-analysis, Behringer *et al*. [30] confirmed that resistance training transferred to gains in sprinting in youth, with greater gains at a younger age, in untrained young athletes, and with a greater intensity of training. In a systematic review, Rumpf *et al*. [16] demonstrated that children who were pre-PHV increased speed most with plyometric training, while children who were post-PHV gained most from combined training (resistance and plyometric training). Later review work by Lesinski *et al*. [18] confirmed combined training as providing the greatest gains in sprint speed for youth. Experimental research has since supported these notions, showing that plyometric training was more beneficial for boys pre-PHV in increasing acceleration, compared to strength training being most beneficial for boys post-PHV, although combined training was equally effective across both maturity groups [31]. More recently, a meta-analysis from Behm *et al*. [17] demonstrated that plyometric training was more advantageous at improving speed in youth compared to strength training, and that gains were greater in children versus adolescents and in untrained versus trained youth populations.

Sprint-Specific Training

Following the principle of specificity, specific-sprint training aims to promote neurological and musculoskeletal adaptations which are velocity and task dependent [32]. Sprint-specific training is commonly understood as performing linear unresisted, resisted, or assisted sprinting interspersed with periods of passive recovery [16]. There is a stark contrast of sprint-specific training research compared to non-sprint specific training. However, the literature that does exist suggests that between 6 – 12 weeks of training can be beneficial for increasing straight-line acceleration and maximal velocity sprinting in youth of varied maturation [33-44]. Given the complex nature of sprinting, unresisted training may refine technique and help promote more effective running patterns [45]. Whereas adding a resistive stimulus to movement in a horizontal plane of motion is commonly referred to as resisted sprinting, which likely facilitates horizontal force production capabilities [46,47]. Various training methods of resisted sprinting exist such as parachutes, weighted vests, belts, and mechanical pulley systems. However, the most commonly used and researched method of resisted sprint training is resisted sled sprinting. The two forms of resisted sled training (RST) that exist are sled pulling and sled pushing, with both being popular in practice but with limited research with sled pulling and little, if any, available for sled pushing.

1.4 Resisted sled training

Although sled pulling and pushing share many commonalities, differences exist in relation to comparative size, shape, anatomical positioning, friction and force application which may in turn lead to changes in mechanics, load prescription and training stimulus. Comparatively both conditions have not been reviewed in the literature, most likely due to the stark contrast of empirical evidence that exists between both modes of RST. The alteration in sprint mechanics during both sled pushing and pulling are likely influenced by the load prescribed on the sled. Increasing sled load in both sled pushing and pulling will result in a reduction in stride length, stride frequency flight time and increases in contact time [48]. Angular kinematics are also affected with resisted sprinting leading to an increase in forward lean. The most common method of prescribing sled load is as a set percentage of body mass (%BM) for all athletes. However, many limitations exist when prescribing load as a set percentage of BM, the amount of between athlete variation in their ability to tolerate load. Therefore, a new method of sled load prescription has been suggested by Cross et al. [49] where load is prescribed based on its effect on decreasing maximal running speed (Vdec) due to the linear relationship between load and velocity. Although the Vdec approach has been examined in adults during sled pulling [49], the approach has not been studied in young athletes or during sled pushing and therefor the reliability and usefulness of the approach need to be determined. Given the varying levels of size, strength and maturation within a youth population, it is expected that the load to cause a given Vdec will vary considerably across athletes, reinforcing the limitations of prescription of load as a set percentage of body mass.

The majority of previous research has examined lighter loads in RST (<43% BM)[50], however more recent research has begun to examine the effect of sled loading at much heavier loads in excess of 80 % BM [51], but no such data exists for young athletes. In adults, researchers have found heavier loads to be superior to lighter loads to acutely increase GRF impulses [46,52] and longitudinal research has found heavier loads superior to lighter or unresisted in terms of improving acceleration phase split times [51]. Lighter loads may be effective during the latter phase of acceleration during the transition to maximum velocity (Vmax), therefore, different loads should be employed during training to improve specific phases of the sprint [50]. However, no research has examined the effectiveness of RST across unresisted, light, moderate and heavy loads on the force-velocity or velocity distance profiles of young athletes. Acceleration and maximum velocity adaptation may be a function of the amount of load applied to the sled. Therefore, one could hypothesize that heavier loading parameters during training may improve the acceleration phase where high horizontal forces are required, whilst light to moderate loading will likely improve the maximal velocity phase due to low horizontal force and higher velocity requirements [50]. Heavier sled loading may be the stimuli needed to produce a targeted adaptation in horizontal force production during the acceleration phase of a sprint [48], but research is needed to confirm or refute this.

1.5 Thesis Rationale

Sprint speed is a critical factor for sporting success in young athletes [53]. The natural development of speed is influenced by maturity and has been shown to be non-linear in youth populations [8,54]. Natural improvements in speed tend to diminish in late adolescence and increases in speed are largely dependent on adaptation to the training methods employed [8]. Sprint specific methods of training have been shown to improve sprint performance in young athletes to a greater extent than non-sprint specific methods [55]. The limited research available supports the notion that heavier RST primarily influences the acceleration phase of the sprint but there is limited research in youth. Resisted sled training may be particularly useful in improving horizontal force production. However, there is a need to establish if the load-velocity profile can be used to individualise load prescription and to further examine how load influences different phases of the sprint and force-velocity profile following RST.

1.6 Purpose of the Research

This PhD was conducted with the purpose of answering the overarching question: "What are the acute and chronic training responses to resisted sled pushing and pulling in young athletes?" The PhD is divided into four primary sections; a review of literature, two acute experimental studies, two longitudinal training studies and a concluding section summarising the findings in a practical and concise manner. The specific aims of the PhD were to:

1) Review and compare the literature related to acute and chronic training response to resisted sled pushing and pulling.
2) Examine the reliability, linearity, between-athlete variation and usefulness of individual load-velocity profiles to prescribe training loads during sled pushing and pulling in young athletes.
3) Assess the effectiveness of unresisted and resisted sled pull and sled push training on sprint performance across a spectrum of individualised loads.
4) Provide practical programming guidelines on how to integrate resisted sled training into an athletes training.

1.7 Structure of the Thesis

In order to fulfil the requirements of AUT pathway two (PhD by publications), all chapters except the first and last were written in the format of a published journal article, with all of those chapters either already accepted for publication (Chapters 2, 3 and 4) or currently under review (Chapters 5, 6 and 7). The work is also supported by a published book chapter (appendix 11). Each chapter commences with a prelude section outlining how each chapter is interlinked to the previous to ensure that the thesis is cohesive. The thesis is divided into eight chapters consisting of four sections designed to answer the overarching question of what are the acute and chronic training responses to resisted sled pushing and pulling in young athletes? A scheme of work is illustrated in Figure 1.1.

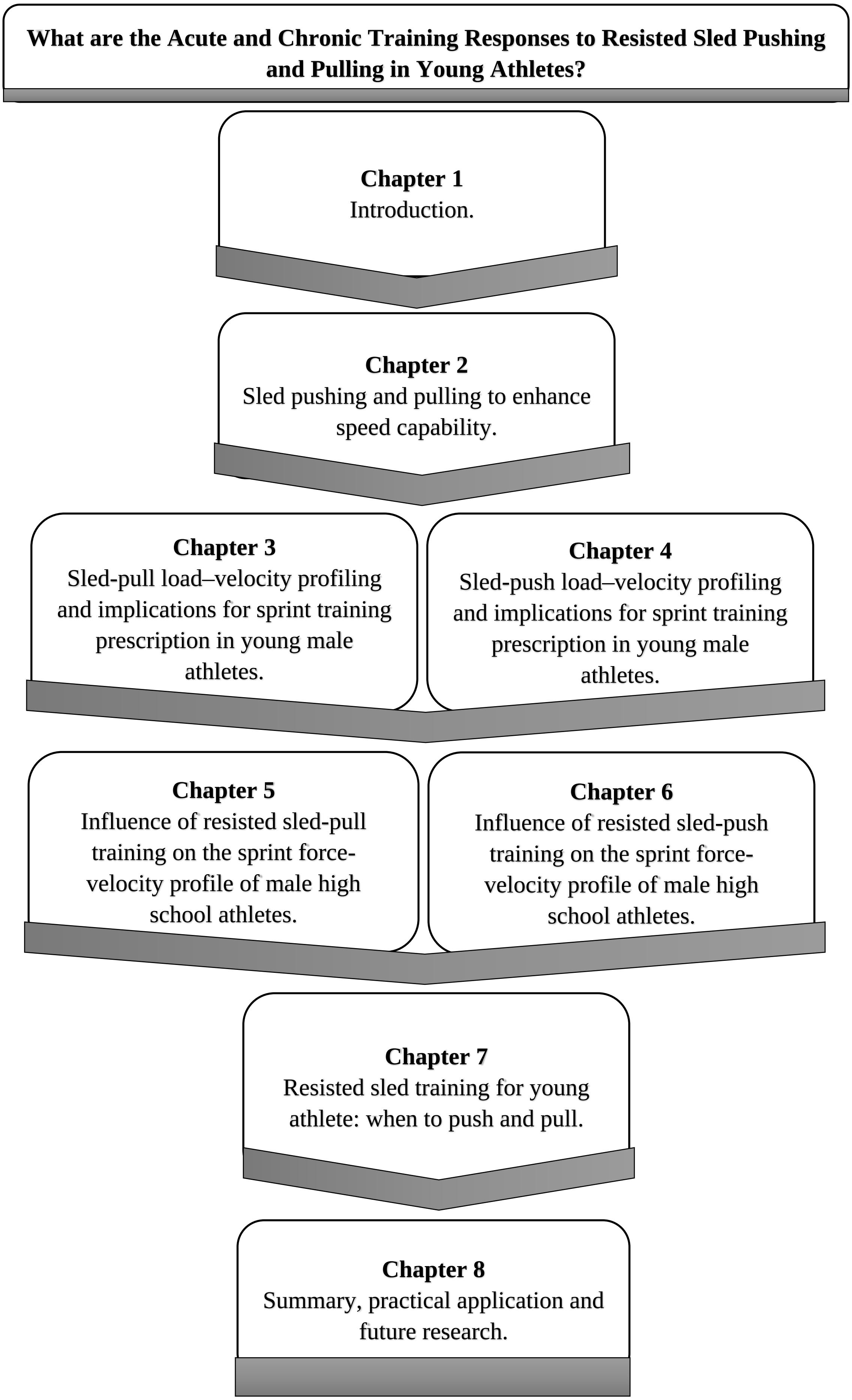

Figure 1.1. Thesis flowchart

CHAPTER 2. SLED PUSHING AND PULLING TO ENHANCE SPEED CAPABILITY

This chapter comprises of the following published paper:

Cahill, M. Cronin, JB. Oliver, JL. Clark, K. Cross, MR. Lloyd, RS. Sled pushing and pulling to enhance speed capability. *Strength & Cond. J.* 2019; 41(4):94-104

2.0 Prelude

Coaches often use resisted sprinting as a sprint-specific mode of training. However, practical guidelines on best practice across youth and adult populations do not exist. The purpose of the following narrative review was to inform practitioners and researchers the loading parameters used and the methods of loading prescription, for both sled pushing and pulling. This review identifies the gaps and limitations in the literature, which sets the foundation and guides the research within this thesis.

2.1 Introduction

Sprinting is a critical factor necessary for individual and team sport success [3]. The success of a sprint is determined by the ability to accelerate, the extent to which maximal velocity is achieved and the ability to maintain that velocity against the onset of fatigue [56]. Team sports codes however such as rugby, Gaelic football and Australian football have been shown to exhibit multiple short distance accelerations upward of over 100 per game, typically between 10 to 20 m [57-59]. In professional soccer players the mean duration of sprints completed during a soccer game are reported to be between 2-4 seconds [60]. Given the recurrence of short distance acceleration in many common field-based team sports, one could argue that the development of this phase outweighs the benefit of time spent isolating the development of maximum velocity (e.g. sprint mechanics) in all but ‘pure’ speed sporting codes. Horizontal force production and the orientation of the force vector are strong influencers of an athlete's ability to accelerate [47,61]. Identifying training methods to improve horizontal force production and the orientation of the force vector, would seem important for the improvement of this motor quality.

The majority of studies that examine training and improvements in sprint speed utilize non-specific forms of training, such as strength, plyometric or combined training methods [62-67]. Those methods have been shown to be effective at improving acceleration and sprint performance [19], which may be partly due to resistance training requiring large amounts of force production during the extension of the ankle, knee and hip (triple extension), replicating movement mechanics of sprinting. There are fewer studies that examine sprint-specific training, but from the studies that do exist it has been suggested that sprint-specific training transfers greater gains to acceleration and speed than non-specific training [68]. Sprint-specific training may include both unresisted and resisted forms of sprinting. Unresisted and light resisted sprinting may provide a speed stimulus while maintaining sprint mechanics [69,70]. Heavy resisted sprint training will provide a different stimulus, overloading force producing capabilities of the athlete [51]. Although the lower limbs will triple extend during vertical resistance and heavy-resisted sprint training, the latter will alter the force orientation, requiring a greater horizontal force vector that may transfer greater training gains to free sprinting. However, until recently research has focused more on light resisted sprint training and less on heavy resisted sprint training.

Sled pulling and sled pushing are two of the most commonly used forms of resisted sprinting. Although they are both forms of resisted sled sprinting, differences in terms of size, shape, force application and friction will most likely lead to changes in mechanics, load prescription and training outcomes. Therefore, this article aims to critique the literature regarding the effect of sled pulling and pushing on sprint performance, to highlight potential differences between the conditions and describe how load prescription can be individualised for specific training outcomes.

2.2 Overview

Both pushing and pulling sleds are training devices that allow variations of external load to be applied during sprinting and sprinting derivatives. Operationally sled pulling and pushing differ primarily in how they provide a posterior and anterior loading stimulus on the athlete. These differences have necessitated different designs, which has resulted in pushing sleds typically being larger and heavier than pulling sleds. Sleds are relatively inexpensive, readily accessible and the resistance can be easily adjusted from light to very heavy loads. Consequently, sled pulling has been a popular method among coaches of numerous sports to improve sprint speed and particularly acceleration performance[50]. Although the use of sled pushing has been used by sports such as American football and rugby as a technical exercise during practice, the use of the sled push for improving sprint performance is a newer training phenomenon. Currently there is very limited research available detailing the use of this form of training especially as it pertains to sprint performance.

Figure 2.1. Sled pulling device

Figure 2.2. Sled pushing device

An overview of the acute cross-sectional studies that have investigated resisted sled pulling and pushing can be observed as supplementary material to this article (Appendix 1). For a detailed review on resisted sled sprint training studies the reader is directed to a recent review by Petrakos et al. [50] There are a number of limitations that the reader should be cognizant of when interpreting the results of the reviewed research. By understanding these limitations, the reader will better appreciate the quality of the research and its generalizability. This in turn will allow for coaches, practitioners and researchers to determine the significance and application of these findings to their respective fields.

Table 2.1. Influence of sled load on spatiotemporal characteristics of sprint performance

Authors	Subjects	Load	Vel	SL	SF	CT	FT
Lockie et al. (2003)	Healthy male field sport athletes (n=23; mean age 23.1yrs)	12.6 %BM 32.2 %BM	↓ 8.7% ↓ 22.8%	↓10% ↓24%	↓ 6% ↓ 6%	↑ 10% ↑19-22%	↓20-25% ↓40-50%
Murray et al. (2005)	Male rugby and soccer players (n=33; mean age 21.1 yr.)	10 % BM 20 %BM 30 %BM	↓ 9% ↓ 16% ↓ 23%	↓ 8% ↓ 8% ↓ 18%	0% ↓ 4% ↓ 6%		
Maulder et al. (2008)	National and regional competitive male track sprinters (n=10; mean age 20 yr.)	10 %BM 20 %BM	↓ 7% ↓ 12%	↓ 6-9% ↓11-12%	↓ 2-1% ↓ 4-3%	↑ 4-7% ↑11-13%	↓ 1-16% ↓12-20%
Alcaraz et al. (2008)	Competitive sprints and long jump athletes (n=18; mean	16 %BM	↓12-14%	↓ 8%	↓ 5%		

	age 22 yr.) (11 male &7 female)						
Alcaraz et al. (2009)	Male competitive track & field athletes (n=26; mean age 20 yr.)	6 %BM 10 %BM 15 %BM	↓ 7% ↓ 10% ↓ 15%				
Rumpf et al. (2014)	Male children (n=35; mean age 13 yr.) (19 Pre PHV & 16 mid/post PHV)	2.5 %BM 5 %BM 7.5 %BM 10 %BM	↓5- 4% ↓ 8-7% ↓ 11- 7% ↓ 14- 9%				
Martinez et al. (2014)	Male competitive sprinters (n=7) and team sport athletes (n=14) (n=21 mean age 18yr)	5 %BM 10 %BM 15 %BM 20 %BM 25 %BM 30 %BM	↓ 4% ↓ 7% ↓ 10% ↓.12% ↓ 14% ↓ 17%	↓ 2% ↓ 4% ↓ 6% ↓ 9% ↓ 10% ↓ 11%	↓ 2% ↓ 3% ↓ 4% ↓ 4% ↓ 5% ↓ 7%		
Kawamori et al. (2014)	Physically active collegiate team sport males (n=10; mean age 28 yr.)	10 %BM 30 %BM	↓ 6.9% ↓ 22.4%			↑ 2.9% ↑ 12.2%	

The authors have identified 41 studies that have examined resisted sled sprinting and its effect on acceleration, maximal velocity, muscle activity and friction coefficients, the majority of which used sled pulling. To the authors knowledge only five studies have examined the effects of sled pushing, Seitz et al. [71] found a sled push of 75% BM with rest intervals of between 4-12 minutes led to greater post activation potentiation in an unresisted sprint over a sled push of 125% BM. Although Waller et al. [72] reported sprint times the emphasis of the study was in relation to blood lactate response of repeated sprint ability. Also, Madigan et al. [73] studied a comparison of muscle activity from sled pushing with the back squat and found higher levels of muscle activity in gastrocnemius during sled pushing. The remaining published papers by Tano et al. [74,75] were conducted using handheld stop watches which have been shown to produce faster times compared to electronic timing systems [76] [77] and published in an open access journal that has been heavily criticized by the British Association of Sport and Exercise Science. Consequently, the research is not considered robust and has been excluded from the supplementary table and will not be discussed further. A wide range of participants has been studied from youth amateur athletes to high-level sprinters. Most research is in male athletes, with limited research in females or youth. Therefore, the transferability of interpretations to wider training cohorts is limited by the available research. The majority of training studies focused on the early acceleration phase between 0-20 m with some authors including max velocity splits between 20 and 50 m. Load has been expressed primarily in terms of absolute load, percentage decrement in velocity and percent body mass (%BM) with the latter being the most common. The load-speed relationship and kinematic and kinetic variables have been examined at loads ranging from 2.5 – 125% of body mass (BM) across different populations. Sprinting acceleration is determined by the expression and orientation of ground reaction forces. Resisted sprinting works by providing resistive stimuli in the effective direction of the sprint. In sled sprinting, the magnitude of this stimulus is determined by the magnitude of loading applied to the sled, friction (sled material, ground, etc.), the towing/pushing velocity (on some surfaces), and to a lesser degree the angle of pull between the athlete and the sled. The application of load provides an additional resistive vector for force to be produced against, meaning an athlete can generate and maintain conditions of (significantly greater) net horizontal force in stable and targetable conditions.

As observed in table 1, the majority of studies published before 2014 utilised lighter loads (<32% BM) with kinematic variables assessed that found reductions in velocity, stride length, stride frequency, flight time and increases in contact time. Changes were also found in angular kinematics at different loads. Consequentially, researchers previously recommended loading parameters should not exceed approximately 13% BM [78] or cause >10 % decrease in max velocity [70] as going beyond this disrupts sprint technique. More recent studies [46,47,79] have examined kinematic analysis of heavier loads that may cause deviations from unresisted sprint technique, but may provide a disparate physical stimulus. Those studies have included kinetic data analysis such as theoretical maximum force (F_0), theoretical maximum velocity (Vo), peak power production (Pmax), horizontal force, vertical force, ratio of forces (RF), ground reaction forces (GRF) and rate of force development (RFD) (see supplementary material). Impulse is the integral of force over the time in which it is applied; a heavier load will require greater forces to be produced over a longer time period during the push-off phase leading to greater impulse when compared to lighter loads. This is shown to be evident in resisted sled training; researchers have found heavier loads superior to lighter loads during resisted sled sprinting to acutely increase GRF impulses [46,47]. Longitudinal research has also found heavier loads superior to lighter and unresisted groups in terms of improving sprint performance [51,80]. Kawamori et al. [47] found that the greater horizontal and propulsive impulses found in the heavier group were mainly due to prolonged contact time and propulsive duration rather than force magnitude as the mean and peak values of propulsive GRFs were not significantly different between heavy and control groups.

2.3 Sled pushing and pulling

Differences between sled pushing and pulling

Researchers have examined the kinematics and kinetics of resisted sled pulling in some detail. The sled pull is consistently reported to reduce an athlete's stride length and stride frequency as load increases [69,81,82]. For example, stride length reduced significantly more with a heavier load of 20% BM (↓11.2%) in comparison to a lighter load of 15% BM (↓6.8%) [83]. Angular kinematics have also been studied during sled pulling and findings show joint angles at the hip and trunk increase compared to unresisted sprinting [81]. Furthermore, trunk angle forward lean has been shown to increase as sled loads increase [83,84]. Although the velocity of the sprint decreases with increasing load, sled pulling may cause an increase in forward lean, which could enhance horizontal force production. Harness attachment can also influence sled pull kinetics and practitioners typically choose between attaching the sled to either the waist or shoulder. Bentley et al. [85] examined the point of attachment for the harness during sled pulling and recommended the waist, stating that it led to greater net horizontal impulses (↑22.5%) when compared to a shoulder attachment (↑17.5%). This is likely linked to different frictional properties of the sled and in the amount of forward lean and foot placement relative to the centre of mass when attaching the sled to the waist and shoulder. It would appear that research is yet to examine the kinematics and kinetics of sled pushing; however, pushing with the arms does appear to further increase forward lean (see figure 3) and alter foot placement, which may favour increased horizontal impulse during pushing.

Figure 2.3. Competitive female sprinter pushing and pulling loads at 33, 66, and 99% BM, respectively. (A) Unresisted sprint, (B) 33%BM sled push, (C) 66% BM sled push, (D) 99% BM sled push, (E) 33% BM sled pull, (F) 66% BM sled pull, and (G) 99% BM sled pull.

The percentage of body mass (%BM) is the most commonly used method for load prescription. The major limitation of this method is that it does not account for the effects of changing friction coefficients. Linthorne and Cooper [86] found substantial differences between the coefficients of friction between four surfaces; synthetic athletic track, natural grass rugby pitch, 3G football pitch and an artificial grass hockey pitch. Significant difference between surfaces also significantly affected the rate of increase in 30 m sprint time [86]. Cross et al. [79] found a linear relationship between friction force and addition of mass, suggesting no effect on the dynamic friction coefficient, but instead found towing velocity a determining factor on overall sled resistance. These factors must be considered, as they will most likely cause a practical difference of the loading experienced by the athlete. In the case of comparing sled pulling and pushing could assume that the application of a given loading protocol could differ for a number of reasons. Push sleds are typically bigger in size and may have a larger surface area of the sled that interacts with the ground, increasing the coefficient of friction and providing a different level of resistance. Given the likelihood of an increased forward lean onto the push sled due to the use of the arms resting on vertically aligned poles (see Figure 2.3 b-d), increased frictional forces between the sled and surface underneath could result. This in turn would reduce the athlete’s velocity during sprinting. The use of an athlete’s arms during sled pulling could assist in the drive phase of acceleration thus increasing the athlete’s velocity. Finally, the anterior position during sled pushing in comparison to posterior position during sled pulling may influence the activation of certain muscle groups and sprinting mechanics, and as a result affect the velocity profile. Depending on design, both types of training offer a different training stimulus. Coaches and practitioners should be aware of the effects of different friction coefficients between all sled devices and the limitations that exist around prescription of loads based on %BM alone; ultimately the same %BM load cannot be assumed to produce the same challenge in a pull versus a push sled exercise or during resisted sprinting on different surfaces.

Careful consideration should also be given to the equipment set up, with factors such as tow rope length and points of attachment to the athlete (shoulder harness v waist belt) during the sled pull, and the length of the vertical poles and hand position during a sled push. These factors, in conjunction with load, will determine force orientation and potentially the subsequent adaptation. Limited research is available examining the effect of waist belt versus shoulder harness and different hand position in sled pushing while sprinting at heavier loads. The use of the waist belt may externally cue an athlete to push their hips into extension, however at very heavy loads as observed in Figure 3g the load may be too heavy and cause the athlete to flex at the waist. The shoulder harness may seem like the obvious alternative; however, the nature of the shoulder straps can cause irritation, pinching and discomfort during sprinting at heavy loads and the increased angle of the tow cord may also negatively influence the kinetics and kinematics of the sprint. It may be that if waist harnesses are used for sled pulling at heavier loading then the practitioner may consider switching techniques to a sled push for heavier loads or loads that cause a greater decrement in max velocity.

A competitive female sprinter can be observed in Figure 2.3, pushing and pulling loads of 33%, 66% and 99% BM respectively. As stated previously comparative analysis between both conditions is limited but general interpretations can be made across loads of the same condition expressed as %BM. Each image is captured at toe off of the stance leg during the 2^{nd} step of both unresisted and resisted sprinting. With regards to the sled pulling, what is noticeable is that the sled setup across loads of 33% and 66% (Figures 2.3e and f) allows relatively similar body positions to the unresisted sprint (Figure 2.3a). With the heaviest load (Figure 2.3g), however, a noticeable change in trunk flexion is observed. In terms of the sled pushing, the equipment set up resulted in the athlete having a greater trunk lean as compared to the unresisted sprint condition (Figure 2.3a), and this posture was maintained across all loads (Figures 2.3b-d). Given that the resistance is based on the same %BM rather than the %BM that caused the same decrement in velocity (compared to unresisted sprinting) it is not possible to directly compare sled pushing and pulling, other than the position of the swing leg thigh and foot relative to the ground is lowered as load increases in both conditions.

There is enough literature suggesting that heavier sled loads and the resultant increased forward lean could lead to an acute increase in horizontal force application while performing resisted sprints[46,47,87]. It is important to consider however that excessive forward lean due to increased load could be detrimental to the transference effect of training. More longitudinal research is needed across different populations. Although, this supposition has been supported in a recent training study by Morin et al. [51] who reported that very heavy sled loads of ~80% BM clearly increased maximal horizontal force production compared to standard unloaded sprint training (ES = 0.80 vs 0.20 for intervention and controls, respectively) and mechanical effectiveness i.e. more horizontally applied force (ES = 0.95 vs -0.11 for controls). One would expect the same sort of adaptation given the posture of the body during sled pushing. The anterior position of the sled push may cause the exercise to be viewed as more of a horizontal strength training exercise given the arms are in a fixed position. By switching from a heavy sled pull to a heavy sled push at loads that cause a greater reduction in unresisted speed (>65%), an athlete may increase hip extension and maintain postural forward lean but sacrifice the use of the arm drive. Although there is a trade off in sprint technique, such reduction in unresisted speed should be viewed as a strength-speed exercise. Lighter loads that cause less of a reduction in speed (<35%) could be viewed as speed-strength exercises given the higher velocities achieved. Practitioners and coaches should prescribe horizontal strength training loads based on an individual's chosen sporting demands; if arm drive is thought important, then sled pulling offers obvious advantages to the athlete. For example, if a track coach has limited time with a sprinter, they may be able to use their time more efficiently by incorporating heavy sled pulling for lower body force application while still working the on the athlete's arm drive as a technical acquisition practice. More in-depth kinematic and kinetic analysis is needed to draw conclusive comparisons between pulling and pushing.

2.4 Loading Parameters

Earlier research investigating resisted sled pulling used lighter resistances, quantified by %BM (~13%) or % decrement in max velocity (Vdec) (~10%)[69,84]. It was advised to avoid loads heavier than those recommended in the research, due a concern of longitudinal interference with sprint kinematics and kinetics. Nevertheless, this theory of negative adaptations from using heavier loading protocols has never been demonstrated. Intuitively it does not make sense to assume the few minutes a week athletes spend resisted sled pulling will negatively influence sprint technique given the amount of time they will also spend in unresisted running. Kawamori et al. [47] and Cottle et al. [46] have found sled pulls of 30% BM and 20% BM led to a significant acute increase in horizontal impulses and propulsive ground reaction force respectively, compared to both unresisted and 10% BM loading. Newtonian mechanics dictates that heavier resistive loads will require greater propulsive impulses (force x time) to overcome the additional load. The increase in propulsive impulses is largely due to prolonged contact time and propulsive duration resulting in increased requirements of force magnitude. Resisted sprint training at heavy loads should be viewed as an exercise to increase horizontal force production through overload rather than a technical sprint exercise. One could assume that the degradation in acute sprint technique as a product of loading during resisted sprinting at heavy loads may be the stimuli needed to produce targeted adaptation in horizontal force production. However, more research is needed examining the kinematic effects heavy resisted sled sprint training has longitudinally on the technical execution of sprinting. More recently post activation potentiation (PAP) has been studied in both sled pulling and pushing conditions [71,88,89]. Contrasting evidence has been reported between PAP sled pulling studies, Whelan et al. [88] reported no significant effect over 10 m, whereas Wong et al. [89] reported a potentiating effect over 0-5 m (1.13 ± 0.08 seconds vs 1.08 ± 0.08 seconds). Both studies examined the potentiating effect of 30%BM during the acceleration phase of a sprint at rest intervals between 1-10 minutes and 2-12 minutes respectively. Post activation potentiation has been studied at much heavier loads, a recent study by Seitz et al. [71] found 20 m sprint performance is potentiated 4-12 minutes following a sled push of 75% BM but found it impaired at 125% BM. As direct comparisons cannot be made between sled pushing and pulling and their effects on sprint performance potentiation, one would assume that heavier sled pulling loads need to be studied.

Only two studies have examined the kinetic effects of a longitudinal training intervention with loads greater than 20% BM [51,80]. Morin et al. [51] and Kawamori et al. [80] both found a larger decrease in sprint times when using heavier loads (43-80%BM) compared to a lighter load (13%BM) or unresisted sprinting. Interestingly, Kawamori et al., [80] found no significant change in horizontal impulses across loading groups. Improvement in speed with a heavy load was attributed to the athlete's learning to direct GRF impulse in a more horizontal direction rather than expressing larger horizontal GRF impulses. Conversely research by Morin et al. [51] reported increased horizontal force production following a heavy sled pull intervention.

In a systematic review of 11 studies, Petrakos et al. [50] found no evidence that resisted sprint training with loads up to 43 %BM or 30 %Vdec was detrimental to sprint acceleration or maximal velocity. They reported differential training effects depending on training status, with resisted sled loads of 10-43 %BM or 10-30 %Vdec improving acceleration performance in untrained subjects. However, whether these benefits were superior to unresisted sprint training for improved accelerative ability was questionable. In strength-trained and team sport athletes it was thought that slightly heavier loads (~20%-43 %BM) were beneficial for improved acceleration, however, once more the benefits over and above unresisted sprint training were not clear. The general recommendation made by Petrakos et al. [50] were that effective sled sprint training blocks should last for ≥ 6 weeks and include two to three sessions per week of 5–35 m sprints, totalling 60–340 m per session. Given the increasingly progressive nature of loading with resisted sled sprinting research in recent years more research is needed with loads that exceed the parameters recommended in the review by Petrakos et al. [50].

An interesting contention of Petrakos et al. [50] was that acceleration and maximum velocity adaptation was a function of sled load. Heavier type sled load training likely improved the initial acceleration phase where high horizontal forces are required, whilst light to moderate loading (<20% BM) will likely improve the maximal velocity phase due to low horizontal force and higher velocity requirements. It was suggested that sled-training load should be based on the training goal (acceleration or maximal velocity), whether the athletes were in a strength/power phase, and/or the individual force–velocity requirements of the athlete. The load an athlete pushes or pulls during resisted sled training should vary and be considered in an annual periodised plan to reflect specific training goals. Heavier loads could be used in preseason phases developing maximum strength capacity and moderate to lighter loads closer to competition to develop power. Whether these contentions are the case and such approaches produce the desired kinematic and kinetic adaptation requires further longitudinal research.

2.5 Training history, strength and maturation

The acute and chronic responses to sled training are likely to be dependent on the physical characteristics of an athlete, and practitioners must consider how an athlete’s attributes will influence their ability to perform a resisted sprint. Slightly heavier relative loads may be required to improve the acceleration of athletes when compared to untrained individuals [50]. When loading sprint and jump athletes with 16%BM during a sled pull, Alcaraz et al. [84] reported that female athletes slowed more than the male athletes (14 v 12%), although the difference was not statistically tested the sex differences can be estimated to be moderate in magnitude. This difference between the sexes will partly reflect differences in body composition; a resistance that is relative to total body mass rather than lean mass will disadvantage females due to their greater levels of body fat. Rumpf et al. [68] reported that for the same relative loads during a sled pull pre-pubertal boys were slowed by 50% more than post-pubertal boys. The same authors also reported in a later paper that while six weeks of sled training improved the speed, stride length, stride frequency, force and power in pubertal boys it had no benefit for pre-pubertal boys [39]. It is not clear if these different acute and chronic responses are solely a result of maturation, differences in the size, strength or training history of youth, or most likely a combination of these factors. What is clear is that the characteristics of an athlete influences both the acute and chronic responses to sled pulling, and therefore, we would expect the same for sled pushing. The available research suggests that maturity, sex and training history are all likely to influence the ability of an athlete to sprint against resistance, and this may be underpinned by differences in size, relative strength and body composition. While the practitioner should not assume that the same load as a %BM will produce the same stimulus in a push and pull, it should also not be assumed that the same %BM load will produce the same stimulus for athletes of differing characteristics. Loads should be prescribed on the extent to which velocity is decreased rather than a set percentage of body mass. Individual athletes will respond to loading differently. Reductions in speed with load will also be influenced by the sled design and friction with any given surface. While it is difficult to understand exactly how each of these factors influence performance an approach that prescribes resisted training based on a given reduction in speed (e.g. 50% reduction in speed), rather than a set percentage of body load, should be better able to provide a consistent stimulus between athletes and conditions.

2.6 New assessment procedures in resisted sprinting

There are a number of devices that can be used to time sprints such as photocell timing gates, radar/laser, video and global positioning units [90]. As with all methods of assessment each has its own limitations, including cost, complexity of set up, analysis and reliability. Recent advances in technology, specifically high-quality handheld cameras such as the iPhone 6, has paved the way for mobile applications such as My Sprint app to assess sprint performance based on the research by Samozino et al. [91]. Recent research [92] found the My Sprint app to be a valid and reliable method to evaluate sprint performance although the time required to analyse each athlete can prove time consuming in a team setting compared to the use of timing gates or radar gun. Such methods can also be used to determine the speed-load relationship during resisted sprints. Assessing the load speed relationship for induvial athletes can provide coaches with valuable feedback for monitoring performance changes and assessing loading parameters over resisted sprint training blocks, for instance to ensure the load employed during training decreases velocity by a desired amount (e.g. 50%). Coaches can also observe the individual differences certain loads have on an athlete's body angle to ensure the desired training adaptation.

This form of profiling an athlete during resisted sprinting for load prescription is less common. Alcaraz et al. [70] developed a regression equation to optimize sled load in accordance with keeping the athlete's maximal velocity above 90% using a radar gun to assess instantaneous velocity. Martinez-Valencia et al. [87] and Petrakos et al. [93] examined the maximum resisted sled load where an athlete can no longer accelerate between 10-15 m and 15-20 m of a 20 m linear sprint using photocell-timing gates. Both studies did not exceed 30%BM during loading. More recently sprint time has been used to construct force-velocity profiles during unresisted sprinting [91], and that process has also been applied to sled pulling [49]. The advantage of this approach is that it allows determination of the load and velocity combination that optimizes power production. Cross et al. [49] assessed puling loads between 20 and 120% of BM. The authors found that the load to optimise power for recreational and elite level sprinters ranged between 69 to 96% of BM dependent on the individual, but more importantly load was optimised at a decrement in velocity of 48-52% for all athletes. Even though %BM has its limitations for load prescription, it can give useful general guidelines to coaches with time constraints and limited resources. However, simple measurement of the load-velocity relationship can allow coaches to individualise loading to a specific velocity decrement and provide a more targeted training stimulus. Coaches and practitioners should take note of the heavier loading parameters found by researchers to optimise power production when planning sled pushing and pulling training.

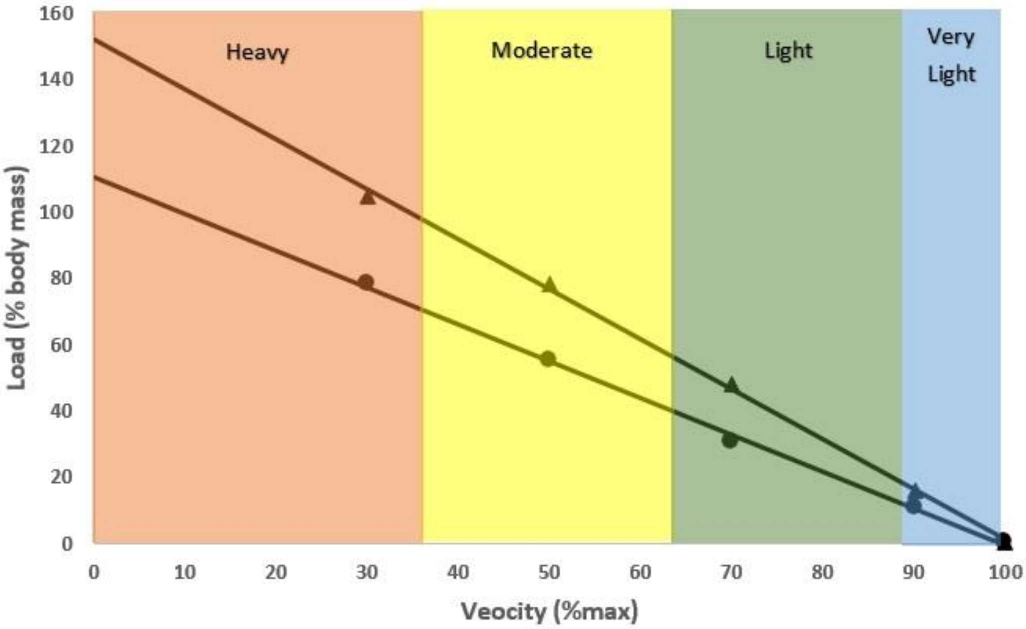

Figure 2.4 Individual load speed relationships of two different athletes sled pushing expressed as %BM

During sled pulling the load-speed relationship has been shown to be linear with power optimized at a Vdec of 50% [49]. While no one has specifically examined power production during sled pushing the load-speed relationship has been shown to be linear [72]. Therefore, it may be assumed that a parabolic power relationship would also occur with power optimized during pushing at a load that reduces velocity by 50%. Figure 2.4 illustrates two different athlete load-velocity profiles during resisted sled pushing, from our anecdotal evidence it is apparent that the same linear relationship exists.

Applying the principles reported by Cross et al. [49] practitioners can measure the load-speed relationship for each athlete across a range of loads and use this to identify the load that decreases speed by 50% and optimises power, this zone is illustrated in yellow in Figure 2.4. In the example shown in Figure 2.4 the load which causes 50% decrease in velocity is 75%BM for the athlete A and 55% BM for athlete B. From this information, heavier or lighter loads can be prescribed based on the individual characteristics (i.e. force or velocity dominant) and the training goal. It is important to note that the load that optimises power may not necessarily be the optimal load that leads to increases in sprint performance. Load prescription may differ dependent on the individual, for example, force dominant athletes may benefit from higher velocity training and vice versa. A certain baseline level of strength (both horizontally and vertically) may need to be established before an athlete can truly utilise loads that optimise power. Heavier loads that cause a greater reduction in unresisted speed (>65%) could be viewed as strength-speed exercises; this zone is illustrated in red in Figure 2.4. Lighter loads that cause less of a reduction in unresisted speed (<35%) could be viewed as speed-strength exercises; this zone is illustrated in green. The load that causes a reduction of 10% in max velocity has been shown not to effect sprint mechanics, this zone is illustrated in blue and could be used by coaches wishing to add a loading stimulus without effecting sprint mechanics.

This type of analysis can offer diagnostic information that both informs adaptation and guides programming, for example, coaches, practitioners and researchers, can use such an approach to make informed decisions on loads prescribed during training to ensure the desired adaptation is achieved. After further analysis of pre and post testing, this approach can provide insight into how different forms of resisted sled training at a given load can alter the force-velocity profile overtime.

2.7 Practical Applications

There is renewed interest in the utility of resisted sled sprinting methods to improve speed ability, given the evolution of knowledge around load (heavy sled work), technique (sled push) and assessment. However, we have also stressed to the reader that there are a number of limitations that the reader should be cognizant of when making sense of the application of research to practice. Practitioners should consider the following when prescribing resisted sled pulling and pushing;

- Resisted sled sprinting provides a stimulus for high horizontal force application and when incorporated into a strength training program it might prove to be a more effective way of improving sprint performance compared to unresisted sprinting or traditional resistance training alone.
- Athlete characteristics, type of sled and type of surface will all influence the amount of resistance experienced. To help account for this, loading should be prescribed on the percentage reduction in velocity for each athlete rather than a set percentage of body mass.

- Reductions in velocity of <10%, <35%, 50% and >65% during resisted sprinting are suggested to reflect high-speed (technical), speed-strength, power and strength-speed stimuli.

CHAPTER 3. SLED-PULL LOAD–VELOCITY PROFILING AND IMPLICATIONS FOR SPRINT TRAINING PRESCRIPTION IN YOUNG MALE ATHLETES

This chapter comprises the following published paper:

Cahill MJ, Oliver JL, Cronin JB, Clark KP, Cross MR, Lloyd RS. Sled-Pull Load–Velocity Profiling and Implications for Sprint Training Prescription in Young Male Athletes. *Sports.* 2019;7(5):119.

3.0 Prelude

As evident from Chapter 2, sled pulling has been widely studied in adult populations. However, a paucity of research exists in youth populations, especially at loads higher than 20% BM. Although the Vdec method for prescription of load was recommended in Chapter 2 due to the limitations found in prescribing load as a percentage of body mass, it has not yet been studied in young athletes. The purpose of this study was to investigate the reliability and linearity of the load-velocity relationship to prescribe load using the Vdec approach during sled pulling in young athletes. A secondary aim was to assess the amount of between athlete variability across a spectrum of loads due to the findings within the literature review of Chapter 2. This chapter provides coaches with insight as to how to prescribe load for sled pulling and the level of between athlete variation that exists in youth populations.

3.1 Introduction

The majority of sprint training research has examined the utility of resistance training and plyometrics as methods to enhance sprinting capability [94-96] rather than sprint-specific training. Sprint-specific training can be defined as training that is specific to the movement patterns and direction of sprinting and it is likely to be more successful than non-specific training in improving speed [97]. A popular method of sprint-specific training is to add resistance while moving in a horizontal plane of motion, commonly referred to as resisted sprint. Recently, researchers have focused on resisted sled sprinting, specifically sled pulling, as a popular and effective method of sprint training [50,98]. As with traditional resistance training, the resistive load used during sled pulling needs to be appropriately prescribed to cause the desired training adaptations. The majority of previous sled pulling research has been studied in adult populations and has prescribed lighter loads (<30% body mass) with the emphasis on ensuring minimal disruption in sprint mechanics and small acute reductions in speed [70,99]. The reliability of resisted sled sprinting has been studied in adult populations [5]. However, the reliability across multiple loads from light to heavy has not been examined in young athletes. More recently, researchers have used heavier loads (>30% body mass) with the intention of improving horizontal force application [51,100,101]. A review of available research in adults demonstrated that heavier loads have been shown to provide greater increase in initial acceleration when compared to lighter loads during resisted sled pulling [50]. However, there is a paucity of research at loads greater than 20 percent body mass (% BM) in young athletes [48]. Thus, limited insights and practical applications for coaches regarding the effects of sled-pull loading are available for young athletes.

Traditionally, the load applied during sled pulling has been prescribed as a % BM [50]. However, due to differences in size, sex, strength, and training history across athletes, this may be inappropriate[48]. The effects on growth and maturation during adolescence can lead to increased variability in response to resisted sprinting [39]. This is particularly the case in athletes where loading by a given % BM has been shown to slow immature boys by 50% more than mature boys [68]. Consequently, prescribing resistance solely as a % BM is likely to provide an even greater varied training stimulus across young athletes in comparison to adults, providing a limited approach which may lead to adaptations which are not necessarily intended. Given the linear relationship between load and decrement in maximal velocity (Vdec), the Vdec approach has been suggested as a more appropriate way to prescribe resistive sprint loads in comparison to % BM [49]. This method has been assessed through multiple and single sprint trial methods of sled load prescription with both methods proving to be effective in calculating the load that optimizes power (Lopt) during sled pulling [49,100]. As per recommendation by Cross et al. [100] a practical application for coaches is to use a combination of both multiple-trial and single-trial methods. Athletes are assessed performing one single maximum sprint and multiple sled sprints across a range of loads, with data then used to establish individual load–velocity profiles. Training can then be prescribed by identifying the load for each individual that causes a given decrement in velocity. This would be particularly useful in young athletes given the increased variability of sprinting kinematics and kinetics associated with maturation [8]. However, there is limited research using this approach, and to the authors' knowledge, there has been very little research describing the responses of young athletes to resisted sprinting.

Using individual load–velocity profiles to prescribe training with a load that causes a given Vdec will provide practitioners with a simple method to standardize the training stimulus across individuals, with different training goals expressed relative to Vdec. The linear load–velocity relationship during resisted pulling leads to a parabolic power-velocity relationship. It has been demonstrated that a Vdec of 50% maximizes power output during sled pulling, and suggested athletes should train with loads that cause this reduction in velocity if the goal is to maximize power gains during sprinting [49]. The recommended loads, however, are far greater than any load ever studied in young athletes. The study also confirmed the linearity of the load–velocity relationship for a range of individuals ($r^2 > 0.97$) and showed that there was large between-participant variation in the load that corresponded to a Vdec of 50% (69–96% BM). While these methods have been verified in adult athletes, it is unknown whether this would be the same for youth athletes given that they undergo anatomical, physiological, and biological variations due to the maturation process [15]. It is possible that the variability may exist to an even greater extent in resisted sled pulling as load increases in young athletes due to the differences in maturity, size, and strength [68].

While the load that optimizes power during sled pulling has been established, other optimization strategies may be needed to achieve different training goals. Extending on the work of Cross et al. [49], different percentages of Vdec may represent training zones for either more speed or force orientated training. Other researchers [70,99] have suggested limiting Vdec to <10% as the load to optimize the maintenance of kinematics while providing a resistive stimulus. More recently, it has been suggested that prescribing a Vdec <35% or >65% may target speed–strength and strength–speed qualities, respectively [48]. Theoretically, it is clear that Vdec can be used to prescribe different training intensities during resisted sprinting, but to date, no research has examined the ability of individual load–velocity profiles to identify optimal loads across a range of training zones in young athletes. The aims of the study are to examine the usefulness of individual load–velocity profiles and the amount of between-athlete variation associated with the Vdec approach to prescribe training loads during sled pulling in young athletes. The authors hypothesize that the Vdec approach is a reliable, effective, and precise way of prescribing sled load to young athletes.

3.2 Methods

3.2.1 Subjects

Seventy male high school team sport athletes from two sports, rugby and lacrosse (16.7 ± 0.9 years; height, 1.77 ± 6.9 cm; weight, 75.6 ± 10.9 kg; post-peak height velocity 1.8 ± 0.8 years and Vmax; 8.08 ± 0.49 m/s) were recruited to participate in this study. All subjects' biological maturity was established as post-peak height velocity (PHV) using a non-invasive method with reliability within 0.5 years of calculating the age at PHV according to Mirwald et al [102]. All subjects had a minimum of one-year resistance training experience and were healthy and injury free at the time of testing. Written consent was obtained from a parent/guardian and assent from each subject before participation. Experimental procedures were approved by the West Chester University institutional ethics committee. The study was conducted according to the Declaration of Helsinki.

3.2.2 Study Design

To determine the load–velocity relationship of unresisted sprinting and sled pulling in youth athletes, seventy male subjects performed one unresisted and three resisted sprints during a familiarization and the subsequent data collection session. A subset of participants (*n* = 15) was used to examine the reliability of sled pulling, repeating the protocol on three separate occasions separated by seven days. Resisted sprints were completed with a range of loads to allow the load–velocity relationship to be modelled. The maximum velocity attained (Vmax) during each sprint was measured via radar gun. Using Vmax individual load–velocity relationships were then established for each subject and used to identify loads that corresponded to a Vdec of 10, 25, 50, and 75%.

3.2.3 Procedures

All subjects reported one week prior to the first data collection, where they were familiarized with the equipment and testing procedures. Testing procedures were completed in dry conditions and on an outdoor 4G artificial turf field with sprint lanes set-up at a cross wind. A randomized counter balance design was implemented during data collection. Subjects were required to abstain from high-intensity training in the 24 h prior to the testing session. Subjects wore running shoes and comfortable clothing. A radar device (Model: Stalker ATS II, Applied Concepts, Dallas, TX, USA) was positioned 10 m directly behind the starting position and at a vertical height of 1 m to approximately align with the subject's centre of mass as per the recommendation of Simperingham et al. [103].

Subjects started from a standing split stance position and sprinted in a straight line for a recorded distance of 30 m with maximal effort for unresisted efforts and 20 m for resisted efforts. A set of cones was placed 2 m in front of each 30 and 20 m markers to ensure maximal effort and achievement of maximal velocity during the sprint. Distances were estimated from pilot testing to ensure Vmax was achieved without inducing additional fatigue. In all sessions, subjects performed a standardized dynamic warm up consisting of sprint mechanics, dynamic stenches and body weight exercises followed by two submaximal effort sprints (70% and 90% of self-determined maximal intensity) before completing maximal effort sprints. A minimum of four minutes and a maximum of six minutes of passive recovery was given between each sprint (unresisted and resisted). Maximum velocity was gathered from the radar gun for all trials. Software provided by the radar device manufacturer (STATs software, Stalker ATS II Version 5.0.2.1, Applied Concepts Dallas, Dallas, TX, USA) was used to collect raw velocity data throughout each sprint.

Unresisted Sprinting Protocol

Subjects were instructed to approach the start line and stand in a split stance with their preferred foot to jump off in front and kicking dominant foot behind. Subjects were instructed to sprint through a set of cones placed at 32 m.

Resisted Sled-Pulling Protocol

Subjects received the same identical setup, instructions, and cues as per the unresisted sprints. The heavy-duty custom-made pull sled (8.7 kg) was placed 3.3 m behind the subject attached to a waist harness by a non-elastic nylon tether. Subjects were instructed to take up all the slack in the tether to ensure no bouncing or jerking as they initiated the sprint. An example of this setup is illustrated in Figure 3.1. Participants were instructed to sprint through a set of cones placed at 22 m. The first resisted trial used an absolute load of 27 kg including the weight of the sled, participants then completed sprints with a minimum of three additional loads increasing in increments of 20% BM (+20, 40, and 60% BM). The load range was based on pilot testing, which determined the range of loads that reduced an athlete's velocity by values above and below 50% of unresisted Vmax and would allow individual load–velocity relationships to be calculated. Loads were selected to fall within the desired velocity decrement thresholds above and below 50% Vmax but not to induce unnecessary fatigue during maximal efforts.

Figure 3.1. An example of the athletes starting stance and setup for resisted sled pulling.

Load–Velocity Relationship and Load Optimization

Maximum sprint velocity was obtained for each unresisted and resisted trial. The individual load–velocity (LV) relationship was established for each participant and checked for linearity. The linear regression of the load–velocity relationship was then used to establish the load that corresponded to a velocity decrement of 10% (L_{10}), 25% (L_{25}), 50% (L_{50}), and 75% (L_{75}), with the slope of the line explaining the relationship between load and velocity. An example of this is illustrated in Figure 3.2.

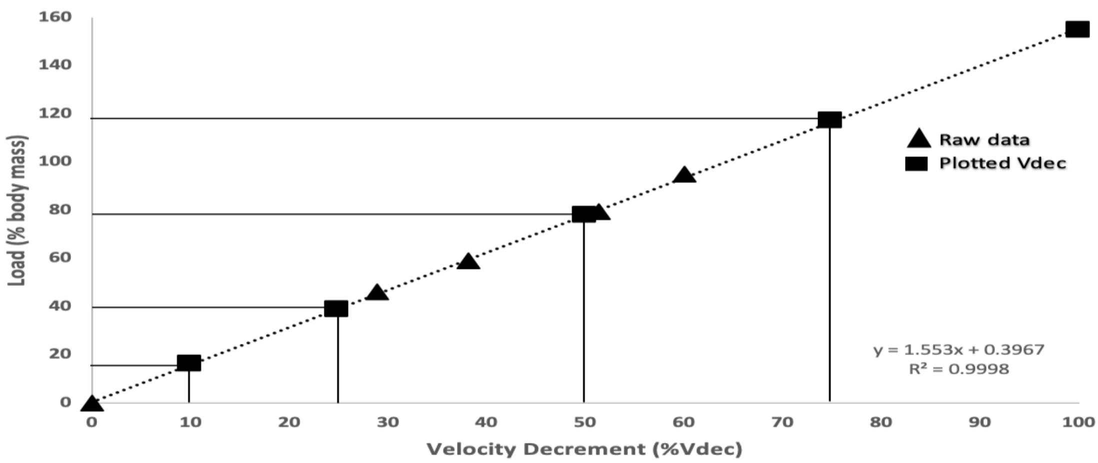

Figure 3.2. An example of the load–velocity relationship for one subject. The raw data (▲) shows the maximum velocity (Vmax) collected during resisted and unresisted sprints. Using the linear relationship between load and velocity, the plotted Vdec (■) shows the calculated loads corresponding to a 10, 25, 50, 75, and 100% decrement in velocity.

<u>3.2.4 Statistical Analysis</u>

Raw data was filtered through custom-made LabVIEW software to determine the maximum velocity of each participant during each sprint. Data were reported as means and standard deviation (SD) to represent the centrality and spread of the data. In the smaller subset of participants (*n* = 15), reliability of Vmax and Vdec were examined across the three different trials by calculating the change in the mean to examine systematic bias. Random variation was then investigated by establishing the relative reliability using an intra-class correlation coefficient (ICC) and absolute reliability using the coefficient of variation (CV). Between-day pairwise analysis of reliability was assessed using Hopkins' online Excel spreadsheet [104]. Simperingham et al. [103] have suggested thresholds for establishing the reliability of sprints using a radar gun as a CV < 10% and ICC > 0.70. The load–velocity relationship of youth athletes was described using statistics from the larger sample of $n = 70$. The strength of linearity of the load–velocity relationship was established for each participant and a one-way repeated measures ANOVA with Bonferroni post-hoc test used to confirm whether differences in Vmax occurred with increased loading. The relationships between variables were determined using Pearson's correlation coefficients. The alpha level was set as $p < 0.05$ with analysis performed in SPSS (Version 23.0). The mean Vdec across all participants at each load was calculated and between-subject variability calculated using 95% confidence intervals.

3.3 Results

The reliability of the variables of interest for the sled pull can be observed in Table 3.1. No consistent pattern of change in the mean was evident across Vmax, Vdec or the slope of the load–velocity relationship across the three trials. The coefficient of variation for Vmax was always <10%, while for the slope of the LV relationship and Lopt it was always <5%. The ICCs ranged from 0.60 to 0.92, with the lowest ICCs associated with Lopt and acceptable relative reliability for the slope of the LV relationship and Vmax. However, when Lopt was expressed in absolute load (kg), very high relative reliability (<0.90) was reported. Pairwise analysis indicated that both relative and absolute random variation were stable across trials.

Table 3.1. The reliability of maximal velocity (Vmax), the load corresponding to given decrements in velocity (Lopt), and the slope of the load–velocity relationship during resisted sled pulling. Results are shown as mean ± SD and reliability statistics (95% CI). CV—coefficient of variation; ICC—intra-class correlation; Vmax—maximum velocity; Lopt—optimal load.

Reliability of sprint variables		**Mean**			**Change in Mean (%)**		**CV (%)**		**ICC**	
		Trial 1	**Trial 2**	**Trial 3**	**Trial 1–2**	**Trial 2–3**	**Trial 1–2**	**Trial 2–3**	**Trial 1–2**	**Trial 2–3**
Vmax (m/s)	Unresisted	7.9 ± 0.5	8.0 ± 0.4	7.9 ± 0.5	1.0 (−1.1–3.1)	−1.5 (−3.1–0.0)	2.8 (2.1–4.4)	2.1 (1.6–3.3)	0.84 (0.64–0.95)	0.88 (0.68–0.96)
	27 kg	6.1 ± 0.8	6.1 ± 0.8	6.1 ± 0.7	−0.6 (−4.1–3.0)	−0.7 (−1.7–3.2)	4.9 (3.6–7.6)	3.1 (2.3–5.0)	0.84 (0.60–0.94)	0.92 (0.79–0.97)
	+20% BM	5.2 ± 0.5	5.2 ± 0.5	5.1 ± 0.6	−1.1 (−3.5–1.4)	−1.0 (−4.1–2.3)	3.4 (2.5–5.2)	4.2 (3.1–6.7)	0.91 (0.75–0.97)	0.87 (0.66–0.95)
	+40% BM	4.4 ± 0.6	4.1 ± 0.4	4.4± 0.6	−5.7 (−10.5–−0.7)	6.2 (1.2–11.5)	7.1 (5.2–11.3)	6.7 (4.9–10.5)	0.72 (0.36–0.89)	0.77 (0.45–0.91)
	+60% BM	3.7 ± 0.6	3.5 ± 0.5	3.8 ± 0.6	−7.1 (−13.4–−0.4)	8.0 (0.7–15.8)	8.6 (6.1–14.6)	9.0 (6.4–14.8)	0.69 (0.24–0.90)	0.73 (0.34–0.90)
Lopt (%BM)	10% Vdec	17 ± 1	17 ± 1	17 ± 1	−1.5 (−4.3–1.4)	0.1 (−2.8–3.0)	3.2 (2.3–5.6)	3.3 (2.3–5.6)	0.71 (0.26–0.91)	0.65 (0.15–0.88)
	25% Vdec	42 ± 4	43 ± 3	42 ± 2	1.2 (−3.0–5.6)	−0.7 (−3.9–2.6)	4.8 (3.4–8.3)	3.7 (2.6–6.4)	0.60 (0.07–0.87)	0.60 (0.08–0.87)
	50% Vdec	84 ± 7	85 ± 5	85 ± 4	1.3 (−2.7–5.5)	−0.6 (−3.7–2.5)	4.6 (3.3–8.0)	3.5 (2.5–6.1)	0.63 (0.12–0.88)	0.64 (0.13–0.88)
	75% Vdec	125 ± 11	128 ± 8	127 ± 5	1.4 (−2.8–5.8)	−0.9 (−4.1–2.4)	4.8 (3.4–8.3)	3.7 (2.6–6.4)	0.60 (0.07–0.87)	0.60 (0.07–0.87)
Slope	Load–Velocity	−1.72 ± 0.15	−1.72 ± 0.08	−1.72 ± 0.06	−0.7 (−4.1–2.9)	0.4 (−1.5–2.4)	4.0 (2.8–6.8)	2.2 (1.6–3.8)	0.71 (0.23–0.91)	0.75 (0.30–0.92)

Load–Velocity Profiling Results

In the large population of young athletes, the average Vmax achieved in unresisted sprinting and with mean loads of 55 ± 3% BM, 75 ± 7% BM, 95 ± 10% BM, and 115 ± 14% BM were 8.1 m/s ± 0.59 s, 5.61 m/s ± 0.56 s, 4.47 m/s ± 0.54 s, and 3.74 m/s ± 0.47 s, respectively. Analysis revealed that Vmax at each load were significantly different to one another ($p < 0.001$). For all subjects, the load–velocity relationship was highly linear ($r > 0.95$), as was the case for the mean data across the group ($r = 0.99$). The mean load–velocity profile together with loads that correspond to a Vdec of 10, 25, 50, and 75% for a large group of youth athletes can be observed in Figure 3.3. Based on the individual load–velocity relationships, the Lopt that corresponded to a Vdec of 10, 25, 50. and 75% (95% CI) were 18 (14–21), 45 (36–53), 89 (71–107), and 133% (107–160) BM. Pearson's correlation coefficients did not demonstrate a significant relationship between Lopt expressed as % BM and variables such as maturity, weight or Vmax.

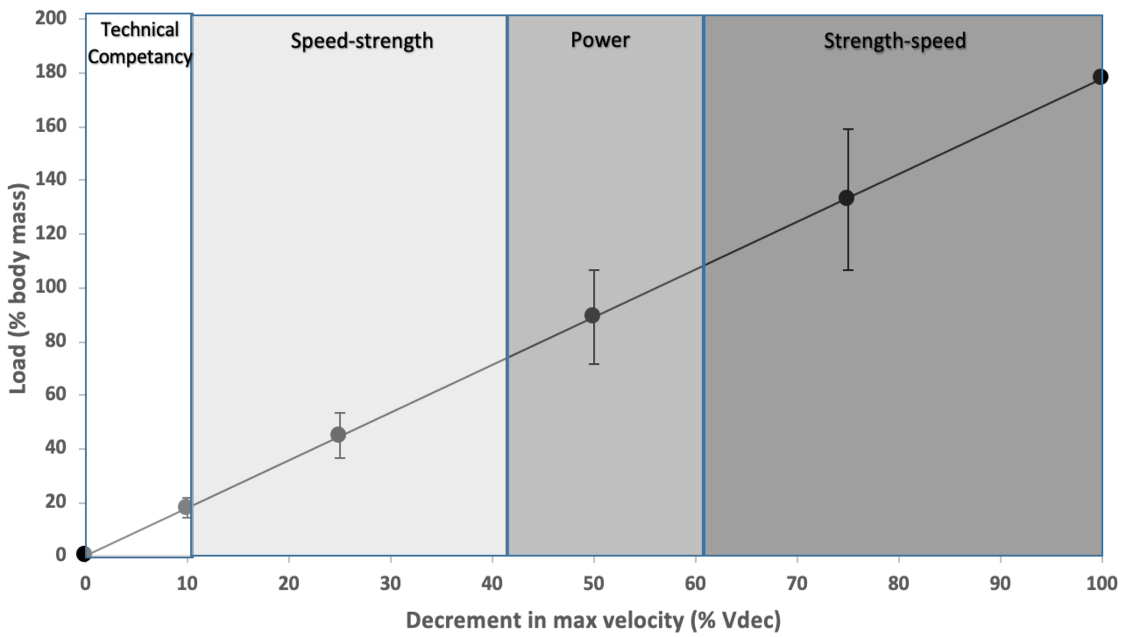

Figure 3.3. The linear mean load–velocity relationship for a group of $n = 70$ youth athletes with the loads that correspond to a decrement in velocity of 10, 25, 50, and 75 representing technical competency, speed–strength, power and strength–speed training zones.

3.4 Discussion

The purpose of this study was to examine the usefulness of load–velocity profiling and the between-athlete variation associated with load prescription during resisted sled pulling in young athletes. The highly linear nature of all individual load–velocity profiles confirms the validity of the approach. The study also established that optimized loads could be reliably identified for different decrements in velocity, suggesting the process can be used to consistently prescribe loads specific to a variety of training outcomes. Importantly, the study also highlights that there is relatively large between-subject variation in the loads that cause a given amount of Vdec. For example, the load that optimizes power, causing a Vdec of 50%, had a confidence interval spanning 71–107%. This individual variability is in agreement with previous research [49] and confirms that prescribing load simply as a given % BM for all individuals would be an invalid approach to prescribe training load in young athletes.

Reliability analysis demonstrated no systematic bias in any of the variables, suggesting the absence of any learning effects, which agrees with previous research in adult populations [49,93,100]. This is the first study to examine the reliability of resisted sled pulling in young athletes. When examining the CV across multiple loads for Vmax, it was found to demonstrate acceptable absolute reliability <10%. Optimizing load might be considered the variable of most interest for resisted sled training prescription, and this had low random variation with CVs < 5%. Intra-class correlation coefficients were acceptable (≥0.70) for nearly all Vmax comparisons. Although ICCs were lower for Lopt, when expressed in absolute loads they demonstrated very high levels (<0.90) of relative reliability. This finding reflects the more homogenous nature of Lopt when expressed relative to body mass versus the more heterogenous nature of Lopt when expressed as absolute load. The high reliability of the optimized loads for each training zone was due to the consistency of the load–velocity profile, with the slope of the individual relationships found to be reliable. Specific conditions of <10, 25, 50, and 75% of Vdec to correspond within zones of technical competency, speed–strength, power and strength–speed have been suggested in this study. However, based on the reliability of the load–velocity slope, researchers and practitioners could identify optimized loads that correspond to alternative target decrements in velocity. Specific Lopts could be reliably prescribed to young athlete's dependent on the phase of the season such as heavier strength–speed zones during pre-season phases and lighter speed–strength zones closer to or within competition.

The high degree of reliability shown in the current study are congruent with previous research examining sled load prescription [49,93]. The lack of systematic bias and stable random variation across trials suggests there were no improvements in reliability across trials, which may be partly due to the familiarization to sled pulling prior to data collection. The results of the current study suggest that individual load–velocity profiles can be reliably used to identify optimized loads across a range of velocities. It is difficult to compare the data of the current study to previous research, due to the lack of research that has used sprint LV profiling in youth athletes. However, force–velocity and load–velocity profiling in other forms of resistance exercises in youth have been shown to be reliable (CV 0.7–6.8; ICC–0.94) [105]. The results of the current study suggest the method can be applied to youth athletes to provide an individualized approach to sled-load training prescription.

Resisted sprint training is a popular method of providing a sprint-specific resistive stimulus. Consequently, resisted sled pulling is a common training method examined by researchers [48,50,98]. However, little uniformity exists for sled-load training prescription.

Unsurprisingly, the addition of greater load caused significant reductions in sprint velocity, allowing the load–velocity relationship to be modelled. The validity of the method is supported given the linear relationship between load and velocity; the current study demonstrated all individuals had a highly linear profile ($r > 0.95$) suggesting the approach can be applied to a large range of athletes. The loads corresponding to a Vdec of 10, 25, 50, and 75% were 18, 45, 89, and 133% BM, respectively. These loads are considerably higher than the majority of the literature previously examining sled pulling and far greater than loads considered heavy (20–30% BM) and very heavy (30+ % BM) in a review by Petrakos et al. [50]. Based on the current findings, loads of 20–30% BM would only be likely to cause modest decrements in velocity (<20%), and what are considered “heavy” loads may need to be reconsidered by both researchers and practitioners.

In agreement with recent research [49], there was a large amount of between-subject variation in Lopt for a given training outcome. Cross et al. [49] reported a range in load of 69–96% BM to cause a Vdec of 50% to optimize power. Similarly, the current study found that a Vdec of 50% resulted in loads ranging from 71–107% BM across a large group of youth athletes and this level of between-athlete variability was consistent across training zones. Although large variability was found between athletes, the Lopt expressed as % BM was not significantly related to weight, PHV or Vmax. Rumpf et al. [39] found significant differences on the effect of loading between pre- and post-PHV athletes; however, the current study found no significant relationship between levels of maturity and Lopt within a cohort of post-PHV athletes. Further research such as the assessment of strength and fat-free mass is needed to better explain the variability between athletes within a group of post-PHV. The findings of this study have major implications for sled-load training prescription for youth populations. While practitioners and previous research have traditionally prescribed loads based on % BM [46,68,106] this approach appears invalid. Based on the current findings, a given load prescribed as a set % BM could reduce the speed of one athlete by up to 50% more than that of another athlete. This would expose athletes to very different stimuli and would potentially lead to different chronic training adaptations. Prescribing training using individual load–velocity profiles provides a method to reliably target a given decrement in velocity within a desired zone of training such as technical competency, speed–strength, power and strength–speed. Furthermore, matching the training zone to the athlete's force–velocity characteristics could potentially yield better training results than simply applying the same resistive load for all athletes [107]. However, further research is needed to better explain the between athlete variation and understand the chronic adaptations when undertaking this approach to sled-pull training in young athletes.

The majority of resisted sprint training research has primarily focused on the high-velocity end of the load–velocity relationship [70,99], ensuring minimal disruption to sprint mechanics by keeping velocity at >90% of the maximum. In the current paper, this has been termed the technical competency zone. This zone may be more applicable to sprinters who want to add a resistive stimulus while still achieving high velocities without affecting sprint mechanics closer to competition. With respect to maturation, technical competency zone training could be best utilized during pre-PHV in young athletes when technical acquisition of sprint mechanics is a priority due to the central nervous system development[108]. Alternatively, athletes of post-PHV who are undergoing increases in androgenic hormones and greater muscle cross-sectional area at the onset of puberty will benefit more with greater resistive loads to stimulate the ability to produce high amounts of horizontal force and impulse [68,101,109]. A recent review by Lesinski et al. [110] suggested that practitioners should emphasize higher intensities and force dominant capabilities of young athletes. Therefore, heavier resistive sled loads may be viewed as an extension of traditional resistance training, but applied horizontally rather than vertically. Recent research has begun to examine the use of heavier sled loads in adults [51,101,107] although apart from the current study only loads of up to 20% BM have previously been used with youth athletes [39,87]. More research is needed to understand chronic training adaptations to heavier sled loads, particularly when prescribed to cause a target decrement in velocity.

3.5 Conclusions

In conclusion, the findings of the current study confirm our hypothesis that the load–velocity relationship is linear during sled pulling in young athletes. The slope and Vdec approach to sled-pulling load prescription were also found to be reliable. However, the load associated with a given Vdec varies across young athletes. The highly linear relationship between load and velocity and acceptable reliability of variables derived from individual load–velocity profiles allow for consistent sled-load training prescription in young athletes during a time in which development of speed is critical. The large variability in the amount of loading required to cause a target decrement in velocity further reinforces the need to adopt an individual approach to sled loading, particularly where the goal is to provide a consistent training stimulus across young athletes of varying size, strength, and training histories. Optimized loads for different training zones were reported in the current study and found to be reliable for technical, speed–strength, power and strength–speed zones. These zones can be used to help coaches periodise sled-loading parameters across a season, such as utilizing strength–speed zones during the off-season and speed–strength zones as competition approaches. Most importantly, the load–velocity relationship was found to be reliable, which means practitioners could reliably prescribe training for any given decrement in velocity. This would allow coaches to qualitatively prescribe individual sled loads and zones of training based on the force–velocity characteristics of the individual athlete. Given the maturational differences across young athletes, sled types and surface practitioners should determine individual load–velocity profiles for athletes in their training environments to better target the desired training adaptation.

CHAPTER 4. SLED-PUSH LOAD–VELOCITY PROFILING AND IMPLICATIONS FOR SPRINT TRAINING PRESCRIPTION IN YOUNG MALE ATHLETES.

This chapter comprises the following accepted paper:

Cahill MJ, Oliver JL, Cronin JB, Clark KP, Cross MR, Lloyd RS. Sled-Push Load–Velocity Profiling and Implications for Sprint Training Prescription in Young Male Athletes. *J Strength Cond Res* (In press).

4.0 Prelude

Two of the main findings of the literature review (Chapter 2) was the overall lack of empirical evidence addressing sled pushing and the limitations in using a set percentage of body mass to prescribe load. Chapter 3 quantified the reliability and linearity of the Vdec approach for sled pulling, and found large between athlete variability across different zones of loading. However, no such data exists for sled pushing and it would be interesting to understand if reliability and linearity are similar between different RST methods. Therefore, the primary purpose of this chapter was to establish the reliability and linearity of the load-velocity relationship using the Vdec approach in sled pushing. A secondary aim was to quantify the between athlete variability across a spectrum of loads, which was hypothesised to be even more pronounced in sled pushing compared to sled pulling given the complexity of the movement, the non-use of the arms and an increased friction coefficient. This chapter provides coaches with insight as to how to prescribe load for sled pushing and the level of between athlete variation that exists in youth populations.

4.1 Introduction

Sprint-specific training can be defined as training that is specific to the movement patterns and direction of sprinting. It is likely to be more successful than non-specific training such as traditional resistance training in improving speed [19,111]. Popular methods of sprint-specific training include adding a resistive stimulus to movement in a horizontal plane of motion, commonly referred to as resisted sprinting. Research has examined different forms of resisted sprinting such as weighted vests and belts [112,113], parachutes [84] and pulley systems [114]. However, sled sprinting is the most commonly researched form of resisted sprinting [48,50] and reflects a form of sprint-specific training that has been shown to improve sprinting performance [51,71,80,106]. The usefulness of sled sprinting as a form of sprint-specific training is likely due to the ability to target distinct bands of horizontal force and velocity output by manipulating loading [46,47,87,101].

In practice two commonly used methods of resisted sled sprinting are sled pulling and pushing. Sled pulling has been more commonly researched across various loads and distances, with a recent review by [50] identifying 11 studies that had examined sled pulling. In contrast there is very limited research available on the acute or longitudinal effects of sled pushing on sprint performance. Waller et al. [72] reported a greater increase in the blood lactate response during loaded sled push conditions over unresisted sprints, while Whelan et al. [71] reported that resisted sled push sprints provided a post-activation potentiation response in a subsequent 20 m sprint. To the authors knowledge these are the only two published studies to examine sled pushing. However, sled pushing has not been examined in youth populations. Research has determined the reliability and the linearity of the load-velocity profile in sled pulling [49,100] and the response of different populations to sled pulling [19,84]. Research by Rumpf et al. [39] demonstrated that mature boys benefited more than immature boys from a resisted sled pull training intervention to enhance sprint capability. However, little is known about the efficacy of resisted sled sprinting as a mode of training at heavier loads in young athletes and no such information exists for sled pushing.

In general, sled pushing is often perceived as a similar method of training to sled pulling. However, differences in force application point (i.e. ‘pushing point) and sled characteristics (size, shape, friction) could in turn lead to alterations in sprint kinematics, kinetics and desired training outcomes when comparing pushing to pulling. For example, if the aim is to train at light loads that don’t change technical markers from unloaded sprinting [70,99], it is likely on most surfaces the base weight of a sled pushing apparatus may exceed that necessary for the aim. Additionally, the anterior position of a push sled and use of the arms would will alter sprint mechanics significantly, irrespective of loading differences in sled pulling. Lighter loads of <10% body mass have been suggested to still allow for technical training during sled pulling [99]. However, the mechanics of sled pushing, specifically the arms, mean that it should not be considered a technical exercise but rather reflecting the use of sled sprinting as a specialized form of horizontal resistance training. More recently, heavier loads have been studied in both sled pushing [71] and pulling [51,101] suggesting greater improvements in acceleration than lighter loads previously studied.

An inverse linear relationship between load and velocity has been confirmed in sled pulling, and it has been suggested that selecting load based on its decrement in velocity (Vdec) could be valuable in training prescription [48,49]. Using such an approach, Cross et al [49] demonstrated that a Vdec of 50% corresponds to a stimulus associated with peak power production during sled pulling, and that the optimal load that causes this level of Vdec within a power zone of training varies considerably across athletes. This variability may also exist to a greater extent in young athletes due to differences in maturity, size and strength. Resisted sled sprinting has been shown to acutely impede immature boys 50% more than mature when load is prescribed as a % of body mass [115]. Therefore, adopting the Vdec method could standardize the training stimulus across a group of young athletes to account for the variability that may exist and the limitations of using % body mass alone to prescribe sled loading. Building on the work of [49], a recent review suggested different percentages of Vdec may represent alternative training zones such as speed-strength (<35% Vdec) or strength-speed qualities (>65%Vdec) respectively [48]. Given the linearity of the load-velocity relationship observed during sled pulling, it is hypothesized that the Vdec approach can also be applied to sled pushing to provide novel insight regarding training prescription during sled pushing. Therefore, the aims of the study are to examine the reliability, linearity and the amount of between-athlete variation associated with the Vdec approach to prescribe training loads during sled pushing in youth athletes.

4.2 Methods

4.2.1. Experimental Approach to the Problem

To determine the load-velocity relationship of unresisted sprinting and sled pushing, a group of young athletes (n = 90) performed one unresisted and three resisted sprints recorded over 30 m and 20 m respectively, at increasing loads during a familiarization session and then again during a data collection session. A subset of participants (n = 16) repeated the protocol on three separate occasions separated by seven days to assess reliability of the method. Resisted sprints were completed with a range of loads to allow the load-velocity relationship to be modelled. The maximum velocity attained (Vmax) during each sprint was measured via radar gun. Using Vmax, individual load-velocity relationships were then established for each subject and used to identify the loads that corresponded to a decrement in velocity of 25, 50 and 75% within speed-strength, power and strength-speed zones respectively.

4.2.2 Subjects

Ninety male high school team sport athletes (16.9 ± 0.9 years; height, 1.77 ± 7.5 cm; weight, 75.7 ± 12.3 kg; and Vmax; 7.71 ± 0.57 m/s) from three sports; rugby, baseball and lacrosse, were recruited to participate in this study. All subject's biological maturity was established as post peak height velocity (PHV) using a non-invasive method of calculating the age at PHV according to Mirwald et al. [116]. All subjects had a minimum of one-year resistance training experience and were healthy and injury free at the time of testing. Written consent was obtained from a parent/guardian and assent from each subject before participation. All risks and benefits of the study were explained prior to data collection. Experimental procedures were approved by West Chester University institutional ethics committee.

4.2.3 Procedures

All subjects reported one week prior to the first data collection, where they were familiarized with the equipment and sprint protocol. Testing procedures were completed in dry conditions on an outdoor 4G artificial turf field with sprint lanes set-up at a cross wind. A randomized counter balance design was implemented on each test day. Subjects were required to abstain from high intensity training in the 24 hours prior to the testing session. Subjects wore running shoes and comfortable clothing. A radar device (Model: Stalker ATS II, Applied Concepts, Dallas, TX, USA) was positioned 10 m directly behind the starting position and at a vertical height of 1 m to approximately align with the subject's centre of mass as per the recommendation of [103]. The radar gun has been validated in human subjects against photocell timing gates at each 10m split within a 100m sprint trial (r^2=0.99) (11).

Subjects started from a standing split stance position and sprinted in a straight line for 30 m with maximal effort for unresisted efforts and 20 m for resisted efforts. Distances were estimated from pilot testing to ensure Vmax was achieved without inducing additional fatigue. In all sessions, subjects performed a standardized dynamic warm up and two submaximal effort sprints (70% and 90% of self-determined maximal intensity) before maximal effort. A minimum of four minutes of passive recovery was given between each trial (unresisted and resisted). Maximum velocity was gathered from the radar gun for all sprints. Software provided by the radar device manufacturer (STATs software, Stalker ATS II Version 5.0.2.1, Applied Concepts Dallas, TX, USA) was used to collect raw velocity data throughout each trial.

Unresisted sprinting protocol

Subjects were instructed to approach the start line and stand in a split stance with their preferred foot to jump off in front and kicking dominant foot behind. Subjects were instructed to sprint through a set of cones placed at 32 m to ensure maximal effort and achievement of maximal velocity during recorded 30m sprint.

Figure 4.1. An example of an athletes starting stance using a custom-made sled push during resisted trials

Resisted sled pushing protocol

Subjects received the same set up and instructions as per the unresisted sprints. A custom-made push sled was placed in front of the start line, between the 0-1 m marks. Subjects were instructed to place their hands at hip height on the vertical poles and lean in towards the sled with elbows bent to a minimum of 90 degrees. Starting stance did not change from unresisted sprints but subjects were reminded to push off the front foot and not to lift the sled base off the ground. Subjects were instructed to sprint through a set of cones placed at 22 m to ensure maximal effort during the 20m recorded resisted sprints. The first resisted trial used was the 27 kg weight of the unloaded push-sled. Two additional loads increasing in increments of 20% body mass were then performed. Pilot testing was carried out to determine the range of loads that reduced an athlete's velocity by values above and below 50% of unresisted Vmax and would allow individual load-velocity relationships to be calculated.

Load-velocity relationship and load optimization

Vmax was obtained for each unresisted and resisted trial. The individual load-velocity (LV) relationship was established for each participant and checked for linearity. The linear regression of the load-velocity relationship was then used to establish the load that corresponded to a velocity decrement of 25% (L_{25}), 50% (L_{50}) and 75% (L_{75}), with the slope of the line explaining the relationship between load and velocity. An example of this is illustrated in figure 4.2.

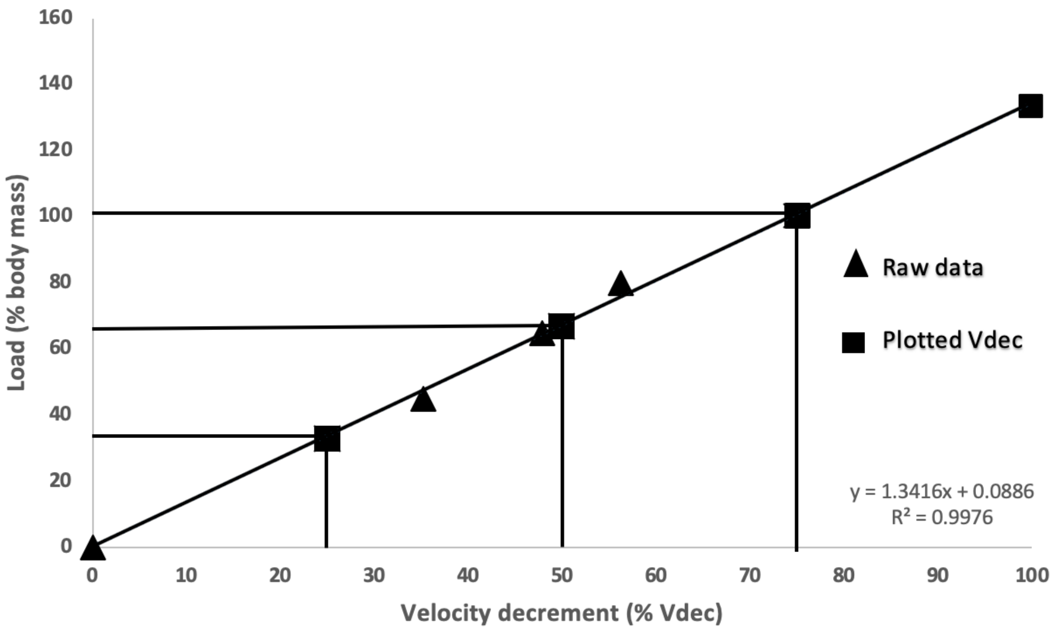

Figure 4.2 An example of the load-velocity relationship for one subject. The raw data (▲) shows the Vmax collected during resisted and unresisted sprints. Using the linear relationship between load and velocity the plotted Vdec (■) shows the calculated loads to cause a 25, 50, and 75% decrement in velocity.

<u>4.2.4 Statistical Analysis</u>

Raw data was filtered through custom made LabVIEW software to determine the maximum velocity of each trial. Means and standard deviations (SD) for Vmax, were used to represent the centrality and spread of the data. In the smaller subset of participants (n = 16), reliability of Vmax, L_{25}, L_{50} and L_{75} were examined by calculating the change in the mean to examine systematic bias. Random variation was then investigated by establishing the relative reliability using an intraclass correlation coefficient (ICC (2,1)) and absolute reliability using the coefficient of variation. Between-day pairwise analysis of reliability was assessed using an online excel spreadsheet [104]. Simperingham et al. [103] have suggested acceptable thresholds for establishing the reliability of a radar to measure sprints as a CV < 10% and ICC > 0.70. The load-velocity relationship of young athletes was described using statistics from the larger sample (n = 90). The strength of linearity of the load-velocity relationship was assessed for each participant and a repeated measures ANOVA with Bonferroni post-hoc test used to confirm whether significant differences in Vmax occurred with increased loading. The alpha level was set as $p < 0.05$ with analysis performed in SPSS (version 23.0). The mean load across all participants at each Vdec was calculated and between subject-variability expressed using 95% confidence intervals. To examine factors that contributed to variability in the load that caused a given decrement in velocity, individual %BM loads at L_{50} were correlated against body mass, maturity, strength (deadlift 1RM), sport played and Vmax, F_0 and Pmax from an unresisted sprint. To further portion out the effect of body mass relationships were also examined with load at L_{50} allometrically scaled using an exponent of 0.67 [117].

4.3. Results

Reliability

The reliability of the variables of interest for the sled push in a subset of sixteen participants can be observed in Table 4.1. No consistent pattern of change in the mean was evident across Vmax, L_{25}, L_{50} and L_{75} or the slope of the LV relationship across the different trials. The CV for Vmax and the slope of the LV relationship was consistently < 10%, while for L_{25}, L_{50} and L_{75} it was always ≤ 5%. The majority of ICCs were within acceptable ranges for Vmax, L_{25}, L_{50} and L_{75} and the slope of the LV, with relationships ranging from 0.68 to 0.91. When L_{25}, L_{50} and L_{75} was expressed in absolute load (kg), extremely high relative reliability (ICC ≥0.99) was observed.

Table 4.1 The reliability of maximal velocity (Vmax), the load corresponding to given decrements in velocity (Lopt) and the slope of the load – velocity relationship during resisted sled pushing. Results are shown as mean ± SD and reliability statistics (95% CI).

	Mean			**Change in mean (%)**		**Coefficient of variation (%)**		**ICC**	
	Trial 1	**Trial 2**	**Trial 3**	**Trial 1-2**	**Trial 2-3**	**Trial 1-2**	**Trial 2-3**	**Trial 1-2**	**Trial 2-3**
Vmax (m/s)									
Unresisted	8.1 ± 0.4	8.1 ± 0.6	8.1 ± 0.5	-0.3	0.1	3.0	2.4	0.76	0.87
				(-2.1 – 1.4)	(-1.3 – 1.6)	(2.3- 4.3)	(1.9 - 3.5)	(0.53 – 0.89)	(0.73 – 0.94)
27Kg	4.7 ± 0.3	4.7 ± 0.3	4.7 ± 0.3	-0.3	-2.5	2.6	4.0	0.83	0.68
				(-2.2 – 1.6)	(-5.2 – 0.3)	(1.9 - 4.0)	(2.9 - 6.4)	(0.56 – 0.93)	(0.32 – 0.87)
+ 20% BM	4.0 ± 0.3	4.0 ± 0.3	4.0 ± 0.3	-1.3	-4.9	5.0	3.9	0.74	0.88
				(-4.7 – 2.3)	(-7.5 – -2.2)	(3.7 - 7.7)	(2.9 – 6.0)	(0.42 – 0.90)	(0.69 – 0.95)
+ 40% BM	3.5 ± 0.4	3.5 ± 0.4	3.5 ± 0.4	-7.1	-1.4	5.7	3.5	0.70	0.86
				(-10.8 – -3.1)	(-3.9 – 1.1)	(4.2 – 8.9)	(2.5 – 5.4)	(0.33 – 0.88)	(0.64 – 0.95)
Lopt (%BM)									
10% Vdec	12 ± 1	12 ± 1	12 ± 1	-1.2	-3.6	5.0	4.9	0.79	0.81
				(-5.1 – 2.8)	(-7.3 – 0.2)	(3.6 – 8.2)	(3.5 – 8.1)	(0.45 – 0.93)	(0.49 – 0.94)
25% Vdec	30 ± 3	30 ± 3	29 ± 3	-1.5	-4.2	3.9	3.9	0.88	0.89
				(-4.7 – 1.7)	(-7.3 – -1.0)	(2.8 – 6.5)	(2.8 – 6.5)	(0.61– 0.96)	(0.66 – 0.97)
50% Vdec	60 ± 7	60 ± 7	58 ± 7	-1.2	-3.7	4.1	3.5	0.86	0.91
				(-4.4 – 2.1)	(-6.4 – -1.0)	(2.9 – 6.7)	(2.5 – 5.7)	(0.63– 0.95)	(0.73 – 0.97)
75% Vdec	90 ± 10	90 ± 10	87 ± 10	-1.4	-3.1	3.6	4.1	0.89	0.88
				(-4.2 – 1.5)	(-6.2 – 0.1)	(2.6 – 5.8)	(2.9 – 6.6)	(0.70– 0.96)	(0.66 – 0.96)
Slope									
Load -Velocity	-25.1± 2.4	-24.2 ± 2.8	-23.7 ± 3.2	-2.1	-2.3	5.6	5.7	0.75	0.82
				(-6.3 – 2.4)	(-6.7 – 2.2)	(4.0 – 9.1)	(4.1 – 9.4)	(0.36 – 0.92)	(0.50 – 0.94)

Load-velocity profiling

Load-velocity profiles ware established on all participants within the study (n=90). In the large population of young athletes, the average Vmax achieved in unresisted sprinting and with mean loads of 37 ± 4 %BM, 57 ± 7 %BM, and 77 ± 11 %BM of body mass were 7.7 ± 1.05 m/s, 5.06 ± 0.76 m/s, 4.30 ± 0.65 m/s and 3.53 ± 0.57 m/s respectively. Analysis revealed that Vmax significantly decreased with each incremental increase in load ($p < 0.001$). For all subjects the load-velocity relationship was highly linear (r > 0.96), as was the case for the mean data across the group ($r = 0.99$). The mean load-velocity profile together with loads that correspond to a Vdec of 25, 50 and 75% for the entire group can be observed in Figure 4.3. Based on the individual load-velocity relationships the load that corresponded to a Vdec of 25, 50 and 75% (95% CI) were 33 (23-42) %BM, 66 (45-85) %BM and 100 (69-131) %BM.

Significant relationships (all $p < 0.05$) were found between the %BM load at L_{50} and body mass (r = -0.60), maturity (r = -0.49), F_0 (r = -0.36), Pmax (r = -0.30), sport played (r = -0.30) and the deadlift 1RM (r = -0.24), leaving only Vmax as a non-significant predictor (r = 0.10, p > 0.05). However, when load was allometrically scaled only sport played (r = -0.27, p < 0.05) and maturity (r = -0.23, p< 0.05) remained as significant predictors, with all other variables reporting correlations of r ≤ 0.09 (p>0.05).

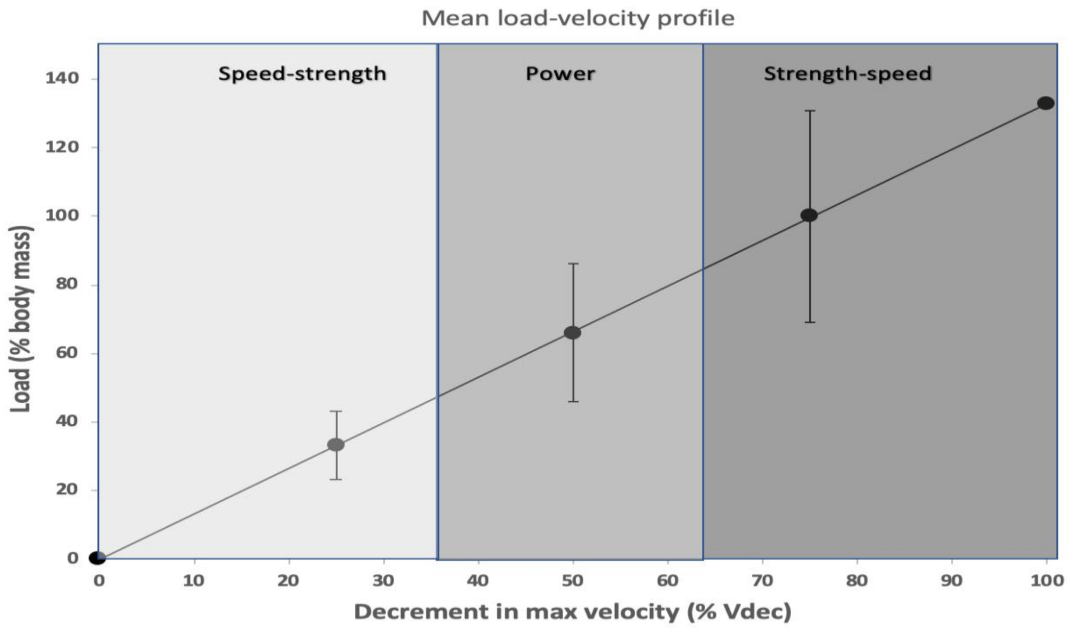

Figure 4.3 The linear mean load-velocity relationship of a group of n = 90 youth athletes with the loads corresponding to a Vdec of 25, 50 and 75% representing speed-strength, power and strength-speed training zones.

4.4. Discussion

This is the first study to examine load-velocity profiles in sled pushing in any population. The underlying rationale for the study was to confirm the linearity of the load-velocity profile and examine the reliability and between-athlete variation associated with prescribing loads for specific training zones. The load-velocity relationship was found to be reliable and highly linear for all participants, and loads could be reliably optimized at a given decrement in velocity to target specific training zones. The current study found a large degree of variability between young athletes performing a sled push; a Vdec of 50% (L_{50}) resulted in a confidence interval for load ranging 45-85 % body mass. This suggests the load required to provide a consistent power training stimulus almost doubles between participants who tolerate load the least to those who tolerate load the most in a youth population, a finding that was consistent across all training zones. This highlights the need for individual prescription based off Vdec rather than % body mass for all individuals.

Multiple studies have found unresisted sprinting using a radar gun to be valid and reliable in adult and youth populations [103,118,119]. However, there is limited research examining the reliability measurements of the radar gun during resisted sprinting, especially in youth populations. This is the first study to assess the reliability of the load-velocity profile of sprint performance in a youth population. The current study found all variables of interest, for both unresisted and resisted conditions, in young athletes to be reliable. There was no systematic change over time, given the low percent changes in the mean between testing occasions across the loads assessed. High reliability was demonstrated for Vmax, L_{25}, L_{50} and L_{75}. The high degree of reliability expressed for loading prescription within specific zones and the consistency of the LV profile in this study are underpinned by the reliability found in the slope of the individual load-velocity relationships, which agrees with previous research on resisted sled pulling [49,93]. All CVs were found to be within an acceptable range of <10% for the three outcome variables of interest across all loads indicating acceptable reliability. L_{25}, L_{50} and L_{75} the variables of most interest for prescription of loads corresponding to different zones of training, was found to be the most reliable variable with CVs <5%. ICC values for Vmax, L_{25}, L_{50}, L_{75} and the slope of the LV relationship were all within acceptable ranges of >0.70 except for one (0.68). Consequently, practitioners can reliably identify specific decrements in velocity to suit the needs of each athlete. A recent study by

Cross et al. [107] concluded that the response to resisted sled pulling may be dependent on pre-training force-velocity characteristics. Therefore, prescription of training loads could be individualized to cater for force or velocity dominant athletes which could result in better sprint training results compared to assigning the same resistive load to the group. Several studies [19,39,115] have demonstrated the benefits of resisted sprinting to young athletes but also highlighted the variability and limitations that exist when using prescription of load based of % body mass. Although the Vdec method can standardize the load across a group, further research is needed to determine the effect sled loading has on the maturation status of young athletes. This will allow coaches and practitioners to better determine how loads can be optimized to ensure enhanced sprint performance throughout adolescence.

While the linear L-V relationship has been confirmed for sled pulling [49,100], this is the first study to confirm that the same is the case for sled pushing. The loads used in the present study of 33, 66 and 100 % body mass are far greater than the majority of the research available in resisted sled pulling [48,50]. However, the validity of the method used within the current study is supported by the reliability and linearity of the load-velocity relationship; all participants demonstrated a highly linear profile ($r \geq 0.96$). Adopting the Vdec method will allow practitioners to identify different training zones during resisted sled pushing, such as speed-strength (L_{25}), power (L_{50}) and strength-speed (L_{75}) [48]. Matching the training zone to the athlete's force-velocity characteristic could potentially yield better training results than simply applying the same resistive load for all athletes [107]. For example, examining adult participants, Cross et al. [49] reported that a load of 69-96% body mass was required to cause a Vdec of 50% and optimize power production. Those findings suggest the amount of load required to cause the same training stimulus increases by ~50% from athletes who tolerate load the least to those who tolerate load the best. What the results also highlight is that the common practice of simply prescribing all athletes the same relative training load (i.e. a set %BM) could potentially induce different training stimuli across a cohort of athletes, with some athletes only slowed a little and others slowed substantially more. Adopting the approach of using the linear load-velocity relationship to prescribe load based on a target Vdec allows the coach to choose a specific load to ensure all athletes are exposed to a specific training stimulus.

Expressing load at L_{50} at a %BM resulted in a number of significant correlations, however, these relationships were largely driven by the effects of body mass. Expressing load as %BM uses a ratio scale method, and during forceful or powerful methods such an approach will likely advantage lighter individuals [117,120]. This was demonstrated in the present study by the negative relationship between body mass and load, with a significant relationship demonstrating that using a ratio scale did not meet the assumption of producing a performance measure independent of body mass [120]. When load at L_{50} was allometrically scaled the relationship with body mass became non-significant, as did relationships with strength, force and power, variables all influenced by mass. Only sport played (lacrosse or rugby) and maturity remained as significant, but weak predictors of load. Sport played may reflect either a selection or training effect, with participants from some sports better able to tolerate load during resisted sprinting. The fact maturity still had a negative relationship with allometrically scaled load is surprising but may reflect the need to account for other maturity and size related factors, such as fat free mass. Currently, little is known about the individual factors that determine the ability of young athletes to tolerate load during sled pushing, with more research needed.

Given the lack of empirical evidence on sled pushing and flaws within prescription of load as % body mass alone, it is hard to draw comparison to other studies. Caution must be used when comparing sled pushing and sled pulling, as although both are forms of resisted sprinting, they may offer different training stimuli. Push sleds are typically bigger in size, have a larger surface area and are likely to increase the athletes Vdec more due to the increased coefficient of friction between the sled base and surface from the placement of the arms onto the vertically aligned poles. The anterior and posterior orientation of the sled may also influence the activation of specific muscle groups. Also given the limited research available on resisted sprinting in youth athletes, it is important to factor in the participant's maturity, mass and strength as they have been shown to impact the extent of variation within a population [68]. Utilizing the same Vdec approach as [49], the current study demonstrated between athlete variability in sled pushing is approximately two-fold higher compared to sled pulling in adult populations although it is important to note various differences in training history, sled apparatus' and experience exist. Therefore, more research is needed to examine the acute and chronic effects of sled pushing on sprint performance in young athletes.

In conclusion, the findings of the current study confirm our hypothesis that the load-velocity relationship is linear during sled pushing in young athlete's. The slope and Vdec approach to sled pushing load prescription were found to be reliable also. However, the load associated with a given Vdec varies considerably across young athletes.

4.5 Practical applications

Given the high linearity and reliability across all variables of interest, practitioners should establish individual load-velocity profiles to prescribe sled push loads for young athletes using the Vdec method. Loads corresponding to Vdec thresholds of 25, 50 and 75% can reliably identify and reflect speed, power and strength training zones to specifically target desired adaptations or cater for individual athlete characteristics. Large between athlete variations exist, thus practitioners must be aware that young athletes can vary considerably in the amount of loading required to cause a given Vdec. This reinforces the need to utilize the load-velocity method to individualize the training stimulus across young athletes during sled pushing.

4.6 Acknowledgements

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CHAPTER 5. INFLUENCE OF RESISTED SLED-PULL TRAINING ON THE SPRINT FORCE-VELOCITY PROFILE OF MALE HIGH SCHOOL ATHLETES.

This chapter comprises of the following paper currently under review:

Cahill MJ, Oliver JL, Cronin JB, Clark KP, Cross MR, Lloyd RS. Lee, JE. Influence of Resisted Sled-Pull Training on the Sprint Force-Velocity Profile of Male High School Athletes. *J Strength Cond Res*. (Under Review)

5.0 Prelude

Chapter 3 set the foundation upon which Chapter 5 is built. The load-velocity profiles assessed across the large sample size in Chapter 3 were used as pre-training data to individualize the prescription of loads using the Vdec approach within this training study. Although Chapter 3 quantified the reliability and linearity of the load-velocity relationship in young athletes, there is currently no existing research examining the training responses across different loads in young athletes using Vdec as the method to individualize load. It is hypothesised that training within the previously identified zones of training (speed-strength, power and strength-speed) will have differential training effects. Chapter 5 therefore investigates the effectiveness of sled pulling across three zones of training and the subsequent change in unresisted sprint force-velocity profiles of young athletes.

5.1 Introduction

The development of sprint speed during childhood is a critical factor for success in young athletes [53]. Natural increases in speed have been shown to be non-linear in youth populations, with a pre and post adolescent spurt due to rapid development of the central nervous system and increase in hormone levels at the onset of puberty respectively [8,54]. Post-peak height velocity (PHV) improvements in speed tend to diminish due to physical maturation, and increases in speed are largely dependent on adaptation to the training methods and stimuli the youth athlete experiences [8]. Researchers have examined both specific and non-specific methods of enhancing sprint performance in young athletes [15,55,110]. Non-specific methods of improving sprint performance primarily include resistance training, plyometric training or a combination of both, with varied responses observed across different stages of maturation [121]. Specific training includes modes of training that more closely reflect the demands and movement patterns of sprinting, such as free, assisted and resisted sprinting [50,122]. Supporting the concept of training specificity, sprint-specific methods of training have been shown to improve sprint performance in young athletes to a greater extent than non-sprint specific methods [55].

Resisted sled pulling is a commonly researched form of resisted sprinting [48,50]. Until recently, researchers commonly recommended an external loading that caused no greater than a 10% decrement in maximum sprint velocity, or a load of ≤12.6 percent body mass (%BM) aimed at minimising disruption to sprint mechanics [70,78]. More recently, researchers have examined the acute influence of sled load on sprint kinetics with loads ranging from light to heavy, to target specific force and velocity training zones during horizontal work [47]. The orientation of the force application in a horizontal direction has also been shown to increase with load during sled pulling [101]. In a recent systematic review of resisted sled pull training studies, Petrakos et al. [50] surmised that heavy sled pull training will improve the initial acceleration phase of a sprint. Positive adaptation to acceleration or maximal velocity is a function of sled load due to production of high horizontal forces at low velocities or vice versa. Recent empirical research supports this suggestion, with soccer players training with a heavy sled load significantly improving acceleration and horizontal force beyond that of a group of players training with unresisted sprints [51]. No research has yet investigated training across multiple loads and intensities to determine the effect on an athlete's force-velocity profile.

A previous limitation of sled pull training is the use of loading based solely on a set percentage of body mass (%BM) for all individuals, as friction, strength, training history and maturation are all likely to influence the relative ability to tolerate external loads [48,68]. An alternative method for loading a sled involves providing participants with a load that causes a given reduction in maximal velocity when compared to unresisted sprinting (Vdec) [49,93]. Using this method, the highly linear relationships between force-velocity and load-velocity during sled pulling has allowed researchers to determine the optimal sled load (Lopt) to maximise power production. [48,49]. Lopt is defined as the load that causes a reduction in maximum sprint velocity by 50% and therefore optimises power production due to the parabolic relationship between power and velocity [49]. Highlighting the need to prescribe individual sled pulling loads, Cahill et al. [123] recently showed that across a large group of youth athletes Lopt ranged from 71-107% BM. Although Lopt targets maximising power (Pmax) production during sprinting, this generalized approach of training using Lopt may not be the most effective in all athletes due to individual characteristics. Cross et al. [107] reported varied responses across individuals following resisted sprint training at Lopt, speculating that this was due to individual variability in pre-training force-velocity profiles. Sled loads that reduce sprint velocity by 25% and 75% have recently been suggested to represent light and heavy loads that target speed-strength and strength-speed qualities of the force-velocity relationship [48]. Increases in sprinting performance may be manipulated through a targeted load within a given zone of training to improve initial acceleration, transitional/late acceleration or maximum velocity. Whether that is the case is unknown, more studies are needed to determine to determine if lighter or heavier loads are required to provide more consistent gains in speed and targeted adaptations within sprinting performance across participants.

In the limited research available on resisted sled pulling in young athletes, maturation differences have been shown to influence adaptation to sled pulling both acutely and longitudinally [68,124]. Immature athletes were found to be slowed by 50% more than mature athletes when working against a load set as a %BM [68]. Post-PHV athletes have also been shown to respond better to resisted sled pulling than pre-PHV athletes over the course of a six-week intervention [124]. The majority of resistance training studies in youth have been conducted using more traditional compound exercises in a vertical plane of motion. Subsequently, a meta-analysis concluded that resistance training at heavier loads produced greater gains in strength, speed and power [110] in young athletes, which may reflect the considerable potential of youth athletes to improve force production [94,125]. If sled pulling is considered as a specialised form of resistance training, then it may be speculated that young athletes will benefit most from sled-pull training with heavy loads, but research is needed to confirm this.

There is currently a paucity of research that has directly compared responses to sled-pull training at a range of loads from across the force-velocity spectrum, and very little research with young athletes. Therefore, the aim of the present study was to assess the effectiveness of unresisted and resisted sled-pull training over an eight-week period at light, moderate and heavy loads in high school athletes.

5.2 Methods

5.2.1 Experimental Approach to the Problem

To determine the effectiveness of resisted sled pulling across a range of loads corresponding to different training zones, 53 male high-school athletes undertook an eight-week, twice weekly, training intervention. Pre-testing was used to determine each athlete's load-velocity profile across unresisted and a number of resisted sprints and then participants were matched for 20 m sprint times and randomly divided into four groups of athletes who trained with either no load, or light, moderate or heavy sled loads. Those loads corresponded to a resistance that reduced velocity by 25, 50 and 75% respectively. Pre and post intervention assessments included jump and sprint testing, with step kinematic and force-velocity profiles calculated during the latter.

5.2.2 Subjects

Fifty-three male high school athletes (16.9 ± 0.8 years; height, 1.75 ± 7.1 cm; weight, 76.4 ± 13.6 kg; and maximum velocity (Vmax); 8.29 ± 0.51 m/s PHV; 1.5 ± 0.7 years) from two sports (rugby and lacrosse) were recruited to participate in this study during their off-season. All participants' biological maturity was established as post PHV using a non-invasive method of calculating the age at PHV according to Mirwald et al. [102]. All participants had a minimum of one-year resistance training experience, although athletes were familiar with resisted sprinting, they had never performed a cumulative structured block of resisted sprint training. All participants were healthy and free from injury at the time of testing. Written consent was obtained from a parent/guardian and assent from each subject before participation. Experimental procedures were approved by an Institutional Ethics Committee.

5.2.3 Test Protocols

Load-velocity profiling

All participants were familiarized with the equipment and testing procedures one week prior to data collection. Testing procedures were completed in dry conditions on an outdoor 4G artificial turf field. A randomized counter balance design was implemented on each test day. Participants abstained from high intensity training in the 24 hours prior to the testing session. Participants wore running shoes and comfortable clothing. A radar device (Model: Stalker ATS II, Applied Concepts, Dallas, TX, USA) collecting data at 46.9 Hz was positioned 10 m directly behind the starting position and at a vertical height of one meter to approximately align with the subject's centre of mass as per the recommendations of Simperingham et al. [103].

Participants started from a standing split stance position and sprinted in a straight line for a distance of 30 m with maximal effort for unresisted efforts and 20 m for resisted efforts. Participants were instructed to sprint through a set of cones that were placed 2 m past the target distance to ensure deceleration was avoided. Following pilot testing, distances were chosen to ensure Vmax was achieved without inducing fatigue. In all sessions, participants performed a standardised dynamic warm up, and two submaximal effort sprints (70% and 90% of self-determined maximal intensity) before completing maximal effort sprints. A minimum of four minutes of passive recovery was given between each sprint (unresisted and resisted). Velocity-time data were gathered via radar using the manufacturer provided software (STATs software, Stalker ATS II Version 5.0.2.1, Applied Concepts Dallas, TX, USA) throughout each sprint.

Unresisted sprinting protocol. Participants were instructed to approach the start line and stand in a split stance with their preferred foot forward. Participants were instructed to sprint as fast as possible with verbal encouragement given throughout each sprint.

Resisted sled pulling protocol. Participants started with an identical set up, instructions and cues as per the unresisted sprints. A heavy-duty custom-made pull sled (8.7 kg) was placed 3.3 m behind the subject attached to a waist harness by a non-elastic nylon tether. Participants were instructed to take up all the slack in the tether to ensure no bouncing or jerking as they initiated the sprint. Again, participants were instructed to sprint as fast as possible with verbal encouragement given throughout each sprint. The first resisted trial used an absolute load of 27 kg, which included the weight of the sled. Participants then completed three additional loads, increasing in increments of 20%BM. The load range was based on pilot testing, which determined the range of loads that reduced an athlete's velocity by values above and below 50% of unresisted Vmax, to provide a broader spectrum of loading parameters and an accurate fit of the linear load-velocity profile.

Load-velocity relationship and load optimisation

Vmax was obtained for each unresisted and resisted trial. The individual load-velocity (LV) relationship was established for each participant and checked for linearity. The linear regression of the load-velocity relationship was then used to establish the load that corresponded to a velocity decrement of 25, 50 and 75%, with the slope of the line explaining the relationship between load and velocity. An example of the raw data gathered from one participants unresisted and resisted trials and its plotted data at corresponding velocity decrements is illustrated in figure 5.1a. As illustrated in figure 5.1b mean loads of 44 ± 4 %BM, 89 ± 8 %BM and 133 ± 12 %BM corresponded to light, moderate and heavy for a velocity decrement of 25, 50 and 75%, respectively.

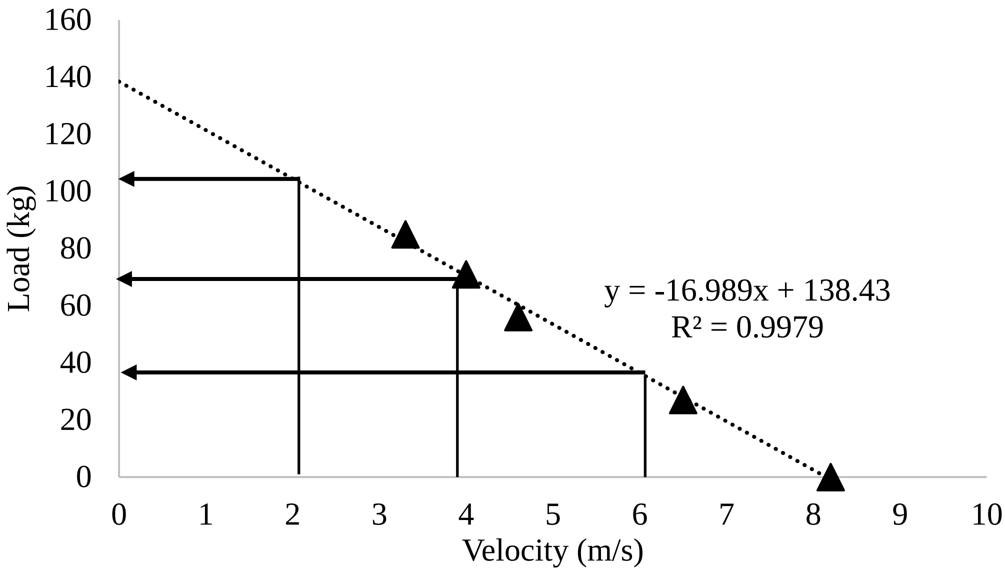


Figure 5.1a. An example of the load-velocity relationship for one subject. The raw data (▲) shows the maximum velocity (m/s) achieved during resisted and unresisted sprints. Using the linear relationship between load and velocity the arrows shows the calculated loads corresponding to a 25, 50 and 75% decrement in velocity.

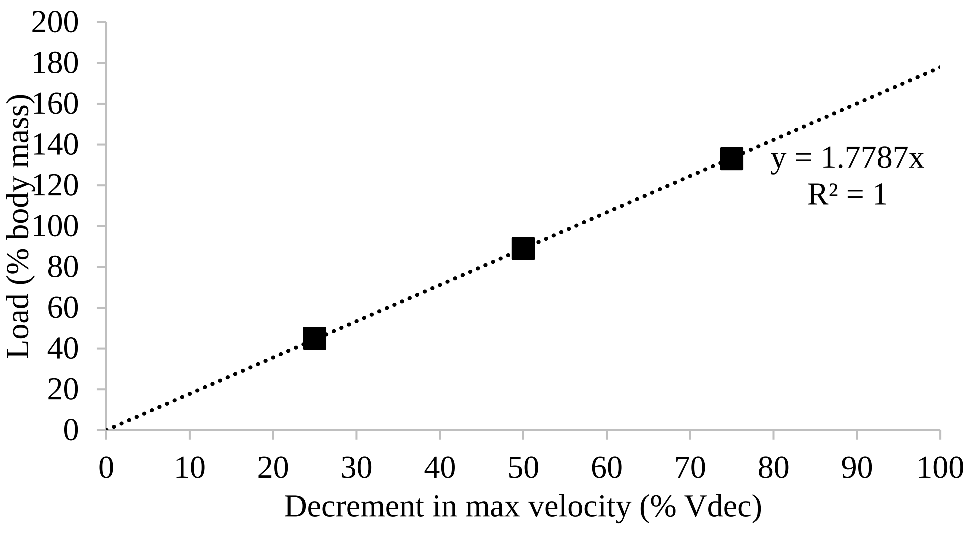


Figure 5.1b. The linear mean load-velocity relationship for all participants with the loads that correspond to a decrement in velocity of 25, 50 and 75%; representing speed-strength, power and strength-speed training zones.

Pre and post intervention testing

Jump testing consisted of both horizontal and vertical jump measures (cm). Both protocols have been shown to be reliable in assessing jump performance in youth [126,127]. During the standing long jump, participants were asked to stand on the start line and jump horizontally as far as possible and then to hold their landing position. A tape measure was then used to measure jump distance from the start line to the rear most heal of the foot upon landing. The countermovement jump used a self-selected depth in which participants were instructed to jump vertically as high as possible and to keep their legs extended while in the air. Jump height was calculated from flight time using an optical measurement system (Optojump, Microgate, Italy). Acceleration sprint testing was assessed using a radar gun, with the set up as per the load-velocity testing except that it took place indoors in a controlled environment over 22 m. The same software provided by the radar device manufacturer used during load-velocity testing was used to collect raw velocity data (Vmax) during each sprint and then fitted with an exponential function. Instantaneous velocity was derived to calculate net horizontal force and power (Pmax). Each linear force-velocity relationship was then extrapolated to calculate theoretical maximum force (F_0). This method has been shown to be a reliable field method to assess force-velocity profiles during over ground sprinting [91]. Sprint force-velocity profiles were then constructed using custom-made LabVIEW software. Contact time (CT) and flight time (FT) during the acceleration phase was captured during both pre and post testing at the 2nd and 3rd steps of the unresisted sprint using an Apple iPhone 6 (Apple, California, USA). Video footage was analysed frame by frame with QuickTime Player 7 Pro for Mac (Apple Inc., Cuptertino, CA, USA).

5.2.4 Training intervention

Participants were matched by speed and randomly allocated between one unresisted and three resisted groups; unresisted (n=12), light (n=15), moderate (n=14) and heavy (n=12) corresponding to a Vdec of 0, 25, 50 and 75% of maximum sprint velocity. The training intervention consisted of two resisted sprint sessions immediately followed by a strength session in the weight room. Participants were provided at least 48 hours recovery time between training days. Additionally, two sport practice sessions were completed on separate days during the week. All athletes abstained from high intensity activity for 24 hours prior to each sled pull training session. Both resisted sprint and strength training protocols followed a linear periodization model, which involved a standard 3:1 mesocycle arrangement (i.e. three weeks of increasing intensity followed by one week of reduced workload) being completed for two consecutive four-week mesocycles. With the exception of their sport practice and specific sled loading using during the sprint training sessions, all groups preformed identical strength training programs. Specific sets and repetitions for resisted sprinting and weight room exercises are provided in Tables 5.1 and 5.2. respectively.

Table 5.1. Sets, reps and weekly total distances for unresisted, light, moderate and heavy training groups

	UNRESISTED			LIGHT (SPEED-STRENGTH)			MODERATE (POWER)			HEAVY (STRENGTH-SPEED)			
Week	**Reps p/w**	**Distance per rep (m)**	**Total distance p/w**	**Reps p/w**	**Distance per rep (m)**	**Total distance p/w**	**Reps p/w**	**Distance per rep (m)**	**Total distance p/w**	**Reps p/w**	**Distance per rep (m)**	**Total distance p/w**	**Rest per rep**
1	6	30	360	6	22.5	270	6	15	180	6	7.5	90	3
2	7	30	420	7	22.5	315	7	15	210	7	7.5	105	3
3	8	30	640	8	22.5	360	8	15	240	8	7.5	120	3
4	6	30	360	6	22.5	270	6	15	180	6	7.5	90	3
5	7	30	420	7	22.5	315	7	15	210	7	7.5	105	3
6	8	30	480	8	22.5	360	8	15	240	8	7.5	120	3
7	9	30	540	9	22.5	405	9	15	270	9	7.5	135	3
8	7	30	420	7	22.5	315	7	15	210	7	7.5	105	3

p/w = per week, m = meters,

Table 5.2. Progressive weight room training program for strength performed by all four groups during the 8-week training intervention.

	SESSION 1					
	Weeks 1 - 4			Weeks 5 - 8		
	Exercise	Sets	Reps	Exercise	Sets	Reps
A1	DB RFESS	3-5	5	BB RFESS	3-5	3
A2	Corrective	3	10	Corrective	3	10
B1	DB bench press	3	8-10	BB bench press	3	6-8
B2	Glute ham iso hold	3	20 sec	Glute ham raise	3	6-8
C1	DB Farmers carry	2	20 m	DB Farmers carry	2	20 m
C2	Inverted Row	2	10-12	Weighted inverted row	2	8-10
C3	Core stability	2	30-60 sec	Cable rotation twist	2	8-10
	SESSION 2					
	Weeks 1 - 4			Weeks 5 - 8		
	Exercise	Sets	Reps	Exercise	Sets	Reps
A1	BB glute raise	3-5	5	BB glute raise	3 -5	3
A2	Corrective	3	10	Corrective	3	10
B1	Chin up	3	8-10	Weighted Chin up	3	3-5
B2	SL pistol squat	3	8-10	Weighted step up	3	6
C1	DB overhead carry	2	20 m	DB overhead carry	2	20 m
C2	Push up	2	10-12	Weighted push up	2	8-10
C3	Core stability	2	30-60 sec	Hanging leg raise	2	8-10

RFESS = rear foot elevated split squat, BB= barbell, DB = Dumbbell, iso = isometric, SL = single leg, m = meters, sec = seconds.

The sled load and sprint distance remained constant for each subject throughout the training intervention. Total work was equated for all resisted groups to that of the unresisted control group by reducing the distance per rep by the same percentage Vdec caused by sled loading. This resulted in sprint distances of 22.5, 15 and 7.5 m for the training groups loaded to cause a Vdec of 25, 50 and 75%, and meant that sprint efforts lasted approximately the same duration across participants in all training groups. All participants had three minutes rest between maximal sprint efforts.

Prior to each training session all participants performed a standardized 10-minute dynamic warm-up was completed, inclusive of submaximal repetitions of sprinting and dynamic mobilization and activation exercises targeting the main muscle groups of the upper and lower extremities. Upon completion of the warm-up all athletes performed sprint training specific to their training group.

5.2.5 Statistical Analysis

Descriptive statistics (mean ± SD) and effect size statistics are reported for all dependent variables of jump and sprinting performance. The data met the criteria for normality and homogeneity. A power analysis was used to determine sample sizes. A 4 x 2 (group x time) repeated-measured ANOVA with Bonferroni post hoc comparisons was used to determine the within and between-group effects for each dependent variable as well as examining interaction effects. An alpha level of $p < 0.05$ was used to indicate statistical significance. Effect sizes (Cohen's *d*) were used to quantify the magnitude of the performance change in each group, with values of 0.20, 0.60 and 1.20 representing the qualitative thresholds for trivial, small, moderate and large effects, respectively [128]. Bayesian statistics were used to further investigate the relative change from pre to post test for all jump and sprint performance variables. Using the Jeffery's prior for parameter estimates, posterior probability of performance improvements for each group and their 95% credible intervals were calculated

5.3 Results

Means ± SD and magnitude of within group changes for all variables in all conditions pre and post intervention are shown in Table 5.3. For all variables there were no significant differences between groups at baseline (*p* > 0.05). Results in Table 3 show that there were main effects of time for all split times, contact time on the second step, F_0 and Pmax (all *p* < 0.01), while Vmax was the only variable to report a significant interaction effect (*p* < 0.05). However, there were clear trends for different responses across the groups when assessing the within-group changes. In terms of the jumps, only the light group significantly improved height (*d* = 0.26). However, the effect of the resisted sled pulling was more marked on the horizontal jump measures with both moderate and heavy groups significantly improving jump performance (*d* = 0.22 to 0.48)

Table 5.3. Means ± SD for all measured variables pre-to-post intervention in youth athletes completing eight weeks of either unresisted, light, moderate or heavy resisted sprint training

	Unresisted			Light			Moderate			Heavy		
	Pre	**Post**	**ES**	**Pre**	**Post**	**ES**	**Pre**	**Post**	**ES**	**Pre**	**Post**	**ES**
VJ (cm)	38.7 ± 5.8	39.2 ± 4.8	0.08	43.1 ± 6.0	44.8 ± 6.3*	0.26	40.9 ± 7.2	41.2 ± 6.9	0.04	42.9 ± 7.8	44.3 ± 7.3	0.18
SLJ (cm)[a]	208 ± 15	208 ± 13	0.01	225 ± 22	230 ± 21	0.22	204 ± 19	213 ± 19**	0.47	215 ± 22	223 ± 23*	0.34
0 - 5 m (s)[a]	1.6 ± 0.12	1.60 ± 0.15	0.01	1.57 ± 0.15	1.51 ± 0.08*	0.43	1.63 ± 0.13	1.54 ± 0.11**	0.71	1.62 ± 0.10	1.50 ± 0.09**	0.84
0 - 10 m (s)[a]	2.42 ± 0.16	2.40 ± 0.17	0.12	2.36 ± 0.18	2.29 ± 0.12*	0.40	2.45 ± 0.18	2.34 ± 0.14**	0.58	2.42 ± 0.12	2.29 ± 0.11**	1.04
0 - 20 m (s)[a]	3.84 ± 0.24	3.79 ± 0.23	0.24	3.73 ± 0.27	3.62 ± 0.19**	0.41	3.85 ± 0.26	3.72 ± 0.19**	0.48	3.77 ± 0.15	3.64 ± 0.16**	0.87
5 - 10 m (s)[a]	0.83 ± 0.05	0.81 ± 0.04	0.39	0.79 ± 0.05	0.78 ± 0.05	0.20	0.81 ± 0.06	0.80 ± 0.04	0.21	0.80 ± 0.05	0.79 ± 0.04	0.18
10 - 20 m (s)[a]	1.42 ± 0.10	1.38 ± 0.08**	0.40	1.37 ± 0.09	1.33 ± 0.08**	0.38	1.40 ± 0.09	1.38 ± 0.07*	0.25	1.35 ± 0.06	1.35 ± 0.07	0.11
2nd step CT (s) [a]	0.17 ± 0.01	0.18 ± 0.00	0.23	0.18 ± 0.01	0.18 ± 0.01	0.30	0.17 ± 0.01	0.17 ± 0.01	0.40	0.17 ± 0.01	0.18 ± 0.01	0.42
3rd step CT (s)	0.16 ± 0.01	0.16 ± 0.01	0.04	0.17 ± 0.00	0.16 ± 0.01	0.43	0.16 ± 0.01	0.16 ± 0.01	0.00	0.15 ± 0.01	0.16 ± 0.01	0.39
FT (s)	0.08 ± 0.01	0.08 ± 0.01	0.04	0.06 ± 0.00	0.06 ± 0.01	0.08	0.07 ± 0.01	0.07 ± 0.01	0.18	0.07 ± 0.01	0.06 ± 0.01	0.44
F_0 (N/kg)[a]	5.5 ± 1.0	5.6 ± 1.1	0.09	5.9 ± 1.4	6.1 ± 1.1	0.22	5.2 ± 0.7	6.0 ± 1.1**	1.08	5.3 ± 0.8	6.3 ± 0.8***	1.19
Vmax (m/s)[b]	8.18 ± 0.44	8.35 ± 0.59	0.33	8.37 ± 0.61	8.60 ± 0.66	0.35	8.31 ± 0.56	8.24 ± 0.55	0.12	8.78 ± 0.79	8.43 ± 0.69*	0.44
Pmax (W/kg)[a]	11.5 ± 2.0	11.8 ± 2.0	0.18	12.7 ± 2.7	13.6 ± 2.5*	0.39	11.3 ± 1.3	12.6 ± 1.7***	1.03	12.1 ± 1.9	13.6 ± 1.9***	0.78

VJ =vertical jump, SLJ = standing long jump, CT = Contact time, FT = Flight time, F_0 = maximal theoretical force, Vmax = maximal velocity, Pmax = maximal theoretical power

[a]Significant main effect of time ($p < 0.01$)

[b]Significant interaction effect ($p < 0.05$)

*Significant within group difference pre-to-post intervention ($p < 0.05$)

**Significant within group difference pre-to-post intervention ($p < 0.01$)

***Significant within group difference pre-to-post intervention ($p \leq 0.001$)

All resisted interventions demonstrated significant within-group improvements for 0 – 5, 0 -10 and 0 – 20 m sprint times. Across 5, 10 and 20 m sprint times there is a clear trend of an increasing effect as load increases; with unresisted sprinting leading to trivial to small improvements *(d* = ≤ 0.24), light loading leading to small improvements *(d* = ~ 0.43), moderate loading leading to small to moderate improvements *(d* = 0.48 - 0.71) and heavy loading leading to moderate improvements *(d* = 0.84 – 1.04). No significant difference occurred in any group from 5 – 10 m, whereas split times between 10 – 20 m significantly improved in unresisted, light and moderate groups but not in the heavy group. No significant differences were observed for any step kinematics, although effect sizes for contact time and flight time were shown to increase with sled load from trivial to small *(d* = 0.00 – 0.44).

With regards to force-velocity profiling, there were significant positive within-group improvements for Pmax for all resisted interventions with moderate effect sizes observed in moderate (*d* = 1.03) and heavy (*d* = 0.78) sled interventions. The cumulative effect of these changes was that Pmax reflected changes in sprint times. A similar trend was observed with F_0 where significant within-group differences and moderate effect sizes *(d* = 1.08 - 1.19) were observed in the moderate and heavy training and interventions. Conversely, a significant reduction occurred for Vmax in the heavy group. Effect sizes for Vmax were trivial to small across all interventions with the greatest effect observed in the unresisted condition *(d* = 0.12 – 0.44). An illustration of the change in velocity over distance and in the force-velocity profile from pre to post training in each group can be observed in figures 5.2. and 5.3. respectively.

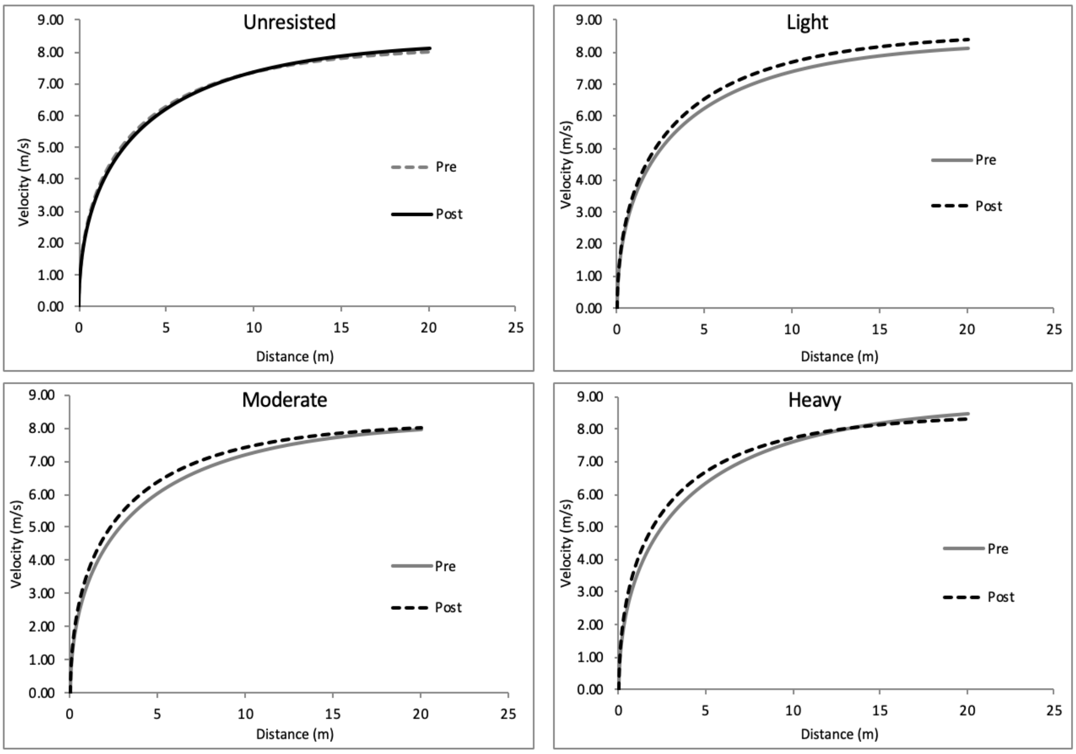


Figure 5.2. Pre to post changes in velocity profiles after an 8-week sled pull training intervention at unresisted, light, moderate and heavy loads.

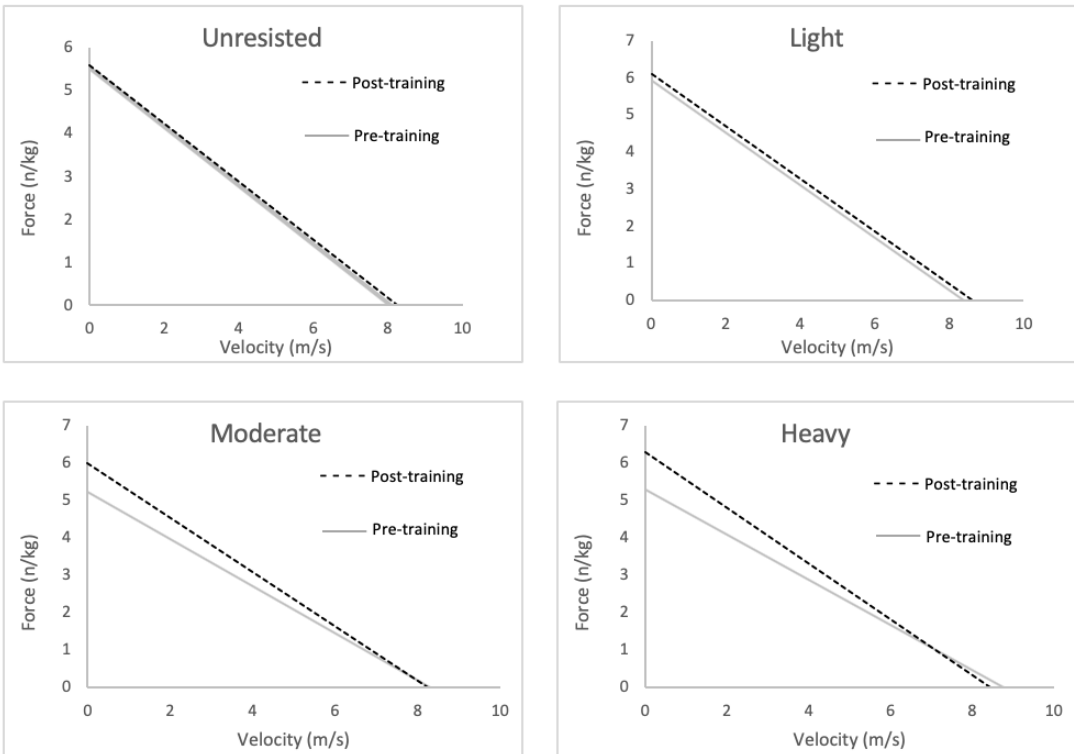


Figure 5.3. Pre to post changes in force-velocity profiles after an 8-week sled pull training intervention at unresisted, light, moderate and heavy loads.

The mean estimated posterior probability of performance improvements for each test variable along with their 95% credible intervals are shown in Table 5.4., with variables with a probability of improvement > 0.75 highlighted in grey. Overall the results confirm that a greater number of variables demonstrated higher probabilities of improvement with increasing load. A higher probability of improved sprint performance, particularly acceleration, was evident at heavier loads in comparison to unresisted or lighter loads. Similarly, the probability of improvement across kinetic sprint variables was generally higher in the moderate and heavy groups. However, a decrease in the probability of Vmax improving was evident at heavier loads.

Table 5.4. Posterior probability (credible interval) of performance variable improvements following unresisted sprint training and resisted sprint training with light, moderate and heavy resisted sled pulling. Grey shaded cells show those variables with a probability > 0.75.

	Unresisted	Light	Moderate	Heavy
	Probability (95% credible interval)			
VJ	0.58 (0.36 - 0.78)	0.73 (0.53 - 0.88)	0.47 (0.27 - 0.68)	0.65 (0.42 - 0.84)
SLJ	0.50 (0.29 - 0.72)	0.67 (0.47 - 0.83)	0.74 (0.54 - 0.89)	0.78 (0.57 - 0.93)
0 - 5 m	0.49 (0.36 - 0.78)	0.70 (0.36 - 0.78)	0.81 (0.36 - 0.78)	0.80 (0.36 - 0.78)
0 - 10 m	0.54 (0.33 - 0.75)	0.73 (0.53 - 0.88)	0.79 (0.59 - 0.92)	0.80 (0.58 - 0.94)
0 - 20 m	0.62 (0.40 - 0.82)	0.78 (0.59 - 0.92)	0.79 (0.59 - 0.93)	0.79 (0.57 - 0.94)
5 - 10 m	0.72 (0.50 - 0.89)	0.59 (0.39 - 0.77)	0.61 (0.40 - 0.79)	0.59 (0.36 - 0.79)
10 - 20 m	0.77 (0.55 - 0.93)	0.81 (0.62 - 0.94)	0.69 (0.48 - 0.86)	0.56 (0.35 - 0.77)
2nd step CT	0.66 (0.44 - 0.85)	0.60 (0.39 - 0.72)	0.68 (0.44 - 0.86)	0.79 (0.64 - 0.95)
3rd step CT	0.50 (0.28 - 0.71)	0.37 (0.18 - 0.59)	0.51 (0.30 - 0.73)	0.67 (0.42 - 0.87)
FT	0.41 (0.21 - 0.63)	0.47 (0.26 - 0.69)	0.52 (0.31 - 0.73)	0.58 (0.34 - 0.80)
F_0	0.51 (0.30 - 0.73)	0.68 (0.48 - 0.84)	0.80 (0.61 - 0.93)	0.79 (0.56 - 0.93)
Vmax	0.33 (0.14 - 0.56)	0.32 (0.15 - 0.52)	0.56 (0.36 - 0.75)	0.69 (0.47 - 0.87)
Pmax	0.59 (0.37 - 0.79)	0.78 (0.59 - 0.92)	0.81 (0.62 - 0.94)	0.80 (0.58 - 0.94)

VJ =vertical jump, SLJ = standing long jump, CT = Contact time, FT = Flight time, F_0= maximal theoretical force, Vmax =maximal velocity, Pmax = maximal theoretical power

5.4 Discussion

The aim of the study was to assess the effectiveness of unresisted and resisted sled-pull training at multiple loads reflective of speed-strength, power and strength-speed zones of training. The main finding of the present study was that moderate to heavy loads resulted in increased sprint performance, particularly during the initial acceleration phase, when compared to unresisted or lighter loads. Changes in sprint split times were reflected in force-velocity profiles, with heavy and moderate sled-pull training significantly improving F_0 and Pmax, while unresisted and lighter loads resulted in small improvements in Vmax. These findings suggest that changes in the sprint force-velocity profile are specific to the training stimulus employed, with heavy sled pulling being particularly effective at improving F_0 and acceleration over 5 m.

Sprint-specific training transferred minimal gains to vertical jump performance, with only the light resisted training group making significant but small gains in performance. Conversely, horizontal jump performance significantly improved with moderate and heavy resisted sprint training, with those groups also making the largest improvement in sprint performance. This supports the notion that horizontal jumps are more strongly related to sprint performance than vertical jump performance [129]. The findings also demonstrate the differential effects of resisted sprint training with different loads on jump performance. These differential effects might be related to the amount of vertical and horizontal force produced with increasing loads, with heavier loads leading to a greater horizontal orientation of force [101]. Therefore, heavy loading through horizontal strength training can be incorporated as a training method to aid horizontal jump performance.

A recent review by Petrakos et al. [50] suggested more sprint training interventions are needed across an array of sled loads to determine the effectiveness of resisted sprint training in comparison to unresisted sprinting. One study examining a single training load of 80% BM and an unresisted control group, found resisted sprinting superior in increasing 5 m and 20 m sprint performance in adult soccer players [51]. Findings from the current study agree with the limited research available; notably, all of the resisted-sprint groups had significant within group improvements in sprint times that ranged from small to moderate in effects size. Interestingly, the magnitude of those effects was greatest over the initial 5 m and increased with greater loading. This indicates that resisted sprinting affected the early acceleration phase, particularly in the groups working with moderate and heavy sled loads. These results are also in line with the limited previous research favouring heavier loads over lighter loads in decreasing 5 m sprint times [47,130]. Gains in sprint performance beyond 5 m were largely the result of the improvement in the initial acceleration phase following moderate and heavy training. Changes in the velocity-distance profiles in figure 2 clearly show training with different resistance influenced the training adaptations, which was reflected in the ability of training at moderate and heavy loads to significantly increase both F_0 and Pmax. However, velocity in the heavy group slightly decreased towards the end of the 20 m sprint reflecting the decreased Vmax post training.

The differential effects of sprint training with either no load or increasing levels of load and the influence on acceleration, speed and horizontal force suggest specificity of training influences force-velocity profiles. Unresisted and light loads slightly increased Vmax, while the opposite occurred at moderate to heavy loads leading to a significant interaction effect. Vmax was significantly reduced at heavy loads. However, F_0 was improved in the moderate and heavy resisted sled training. Pmax did not change with unresisted sprinting, although, small changes were observed with light resistance and moderate changes with moderate and heavy resistance. The current study supports previous research by Cross et al. [107] and Morin et al. [51] that training responses are specific to the loading used during resisted sprint training, leading to specific adaptations across the sprint force-velocity spectrum. Results suggest young athletes will improve their initial acceleration and associated underlying mechanical determinants (F_0 and Pmax). Training programs with an emphasis on improving initial acceleration for team sports athletes should preferentially train with relatively heavy loading regimes. This finding is in line with review work by Lesinski et al. [110], which concluded that non sprint-specific resistance training in a vertical plane of motion was most effective for young athletes when completed at heavy loads corresponding to 80-89% of one-repetition max. The additional resistive stimulus at heavier loads during sled pulling in a horizontal plane of motion combined with the potential of adolescent athletes to increase force application appears to provide an optimum training scenario to improve acceleration. However, practitioners may want to ensure gains in acceleration are not at the expense of maximal sprint speed, in which case young athletes may need to be exposed to sprint training with no or lighter loads. Future research should examine the influence of resisted sled training across a range of loads on the sprint kinematics at maximum velocity.

Probability statistics confirmed that participants were more likely to experience positive improvements in performance when working against heavier loads. The number of variables showing a probability of improvement >0.75 was one for unresisted sprinting, three for training with a light resistance, five variables with a moderate resistance and seven variables with a heavy resistance. The probability of acceleration performance improvement was much greater in light, moderate and heavy groups [47,87] compared to unresisted sprinting. This improved sprint performance has been observed previously [51], however, this is the first intervention study to use loads across three different zones of training at 25, 50 and 75% of velocity decrement in any population, and the first resisted sprint training study to go above a resistance of 10%BM in young athletes. Although participants were familiar with resisted sled pulling, this was the first cumulative training block of such sprint specific training. The novelty of a horizontal strength training stimulus at such heavy loads applied to a cohort at a stage of maturation (~peak weight velocity) in which adaptation to resistance training has been shown to produce favourable results proved to be beneficial [131]. The findings suggest that practitioners will increase the probability of improving sprint performance, specifically initial acceleration by using heavier sled loads than previously studied in young athletes. It may be that those probabilities can be further improved by matching the resistance and training zone to an athlete's initial force-velocity profile [107], however, further research is needed to confirm this.

The aim of the present study was to assess the effectiveness of unresisted and resisted sled-pull training at light, moderate and heavy loads in high school athletes. While all groups exhibited improvements, there was a clear trend for greater and more consistent adaptations with heavier sled loads within a strength-speed zone of training. Changes in sprint performance and velocity-distance profiles were also specific to the force-velocity stimulus of training, with the unresisted and light training group making slight gains in Vmax, all resisted groups improving sprint times and Pmax, and moderate and heavy training groups increasing F_0. Cumulatively, the results show that the greatest gains in short distance sprint speed were made in response to training against heavier external resistances at or in excess of 50% Vdec.

5.5 Practical Applications

Post-PHV males with limited history of resisted sprinting appear to respond favourably to moderate and heavy resisted sprint loads over the course of a short-term training intervention. Thus, in addition to facilitating the correct teaching of acceleration mechanics, heavier external loads may reap the greatest benefits in improving sprint acceleration in as little as 8-weeks of training. The manner in which chronic exposure to resisted sprinting within a longitudinal, periodised training plan influences force-velocity-power (F-V-P) characteristics remains unknown; however, practitioners are encouraged to routinely manipulate the resisted loading to foster ongoing adaptation in performance. The current study also supports the notion of adaptations being specific to the imposed demands, with heavier loads appearing to favour horizontal force production during the early acceleration phase (0 – 10 m), whereas lighter loads and unresisted sprinting benefitting the later phases of acceleration (10-20 m) and maximum velocity. Thus, much like other aspects of strength and conditioning provision, practitioners are encouraged to prescribe resisted sprinting in light of the unique F-V-P needs of the young athlete (i.e. increase F_0 or Vmax).

CHAPTER 6. INFLUENCE OF RESISTED SLED-PUSH TRAINING ON THE SPRINT FORCE-VELOCITY PROFILE OF MALE HIGH SCHOOL ATHLETES

This chapter comprises the following paper currently under review:

Cahill MJ, Oliver JL, Cronin JB, Clark KP, Cross MR, Lloyd RS. Influence of Resisted Sled-Push Training on the Sprint Force-Velocity Profile of Male High School Athletes. *Scand J Med Sci Sports.* (In press)

6.0 Prelude

Chapter 4 set the foundation upon which Chapter 6 is built. The load-velocity profiles assessed across the large sample size in Chapter 4 were used as pre-training data to individualize the prescription of loads using the Vdec approach within this training study. Although Chapter 4 quantified the reliability and linearity of the load-velocity relationship in young athletes during sled pushing, there is currently no existing research examining the training responses across different loads in young athletes using Vdec as the method to individualize loading. It is hypothesised that training within the previously identified zones of training (speed-strength, power and strength-speed) will have differential training effects on the force-velocity profile. Chapter 6 investigates the effectiveness of sled pushing across three zones of training and the subsequent change in unresisted sprint force-velocity profiles.

6.1. Introduction

Sprint speed and its development throughout maturation is a crucial characteristic of athletic performance in team sport competition [132]. Various training methods and modalities exist to develop and enhance speed capability in young athletes [55]. Coaches have employed both non-sprint specific and sprint specific training methods with varying responses in young athletes [124,133,134]. Sprint specific training has largely proven more effective than non-sprint specific training, with the greatest effects generally observed over shorter distance acceleration [19,50]. However, some modalities of training have not received much research attention despite widespread use by practitioners. One such method of sprint-specific training is resisted sprinting in the form of both sled pulling and sled pushing, with the latter much less researched [48].

Anecdotally, sled pushing is a common training method utilized by coaches in team sport settings such as rugby and football. While research using the method is relatively uncommon, sled pushing has been examined in relation to post activation potentiation and blood lactate response in adults in which relatively heavy loading parameters were used [71,72]. A recent study by Cahill et al. [135] examined the reliability and variability within sled pushing concluding that loads can be reliably prescribed to young athletes, with the caveat that the loading response is highly individualized. However, there is a paucity of longitudinal research examining the effectiveness of sled pushing in improving sprint performance. Although sled pushing is viewed as a similar method to sled pulling, many differences exist (e.g. size, shape, friction and anterior positional orientation of the sled) which likely result in unique kinematic and kinetic changes[48]. Only one study exists on resisted sled pushing in young athletes and although it found the prescription of load reliable for post peak height velocity (PHV) athletes; a greater degree of between-participant variability in load was found in sled pushing in comparison to sled pulling when reported as the percentage of body mass (%BM) required to cause a given decrement in velocity[123]. The most notable difference between push and pull conditions is the use of the arms to apply force and overcome inertia during the initial first step of the sprint is unique to sled pushing. Therefore, sled pushing should be viewed as a unique and specialised form of horizontal resistance training [135].

Given the horizonal nature of resisted sled pushing, the same limitations exist as observed in sled pulling with regard to prescription of load as a set %BM in adult and youth populations [49,68,123,135]. The high degree of variability of sled load tolerance in young athletes could be due to a combination of maturation, training history and strength[135]. An alternative method of sled loading is to prescribe load based on the decrement in maximal sprint velocity (Vdec) with increases in load [49]. This method uses the known linear relationships between force and velocity and load and velocity, which have been shown to exist for sled pulling [100,123] and more recently, sled pushing [135]. Cahill et al. [135] suggested light, moderate and heavy loading parameters at sled pushing loads corresponding to 25, 50 and 75% Vdec to represent speed-strength, power and strength-speed zones respectively, but further research is needed to confirm the effectiveness of training within these zones. Categorising sled-pushing as a horizontal strength training exercise might suggest that training would be most effective at heavier loads, particularly with young athlete's where there is a large potential to develop force production [94]. Resisted sled push training at different loads may have differential transference effects to the force-velocity and velocity-distance relationships during unresisted sprinting.

There is currently a paucity of research that has directly compared responses to sled-push training at a range of loads from across the force-velocity spectrum, and no research with young athletes. Therefore, the aim of the present study was to assess the effectiveness of unresisted and resisted sled-push training at light, moderate and heavy loads in high school athletes. The authors hypothesise that training at a heavier load in young athletes will lead to greater gains in horizontal force production and velocity over the initial period of a sprint.

6.2 Methods

6.2.1 Participants

Fifty male high school athletes (16.6 ± 0.8 years; height, 1.75 ± 7.1 cm; weight, 74.3 ± 11.5kg; and Vmax; 8.31 ± 0.58 m/s PHV; 2.3 ± 0.8 years) from two sports (rugby and lacrosse) were recruited to participate in this study during their off-season. All participants biological maturity was established as post-PHV using a non-invasive method of calculating the age at PHV [102]. All participants had a minimum of one-year resistance training experience, although athletes were familiar with resisted sprinting, they had never performed a cumulative structured block of resisted sprint training. All participants were healthy and injury-free at the time of testing. Any athletes who were rehabilitating a previous lower body injury within the last 6 months were excluded from the study. Written consent was obtained from a parent/guardian and assent from each subject before participation. Experimental procedures were approved by West Chester University Institutional Ethics Committee.

6.2.2 Test Protocols

Load-velocity profiling and prescription

All participants were familiarized with the equipment and testing procedures one week prior to data collection by performing two maximal effort repetitions at loads corresponding to light, moderate and heavy. Load-velocity profiling and prescription of loads was conducted using unresisted and resisted trials as described by Cahill et al. [135]. A radar device (Model; Stalker ATS II, Applied Concepts, Dallas, TX, USA) was positioned 10m directly behind the starting position to determine the maximum velocity (Vmax) of both unresisted and resisted trials. The range of selected loads at increments of 20% was based on pilot testing that reduced an athlete's velocity by values above and below 50% of unresisted Vmax.

Pre and post intervention testing

Jump testing consisted of both horizontal and vertical jump measures. Both protocols have been shown to be reliable in assessing jump performance in youth populations [126,127]. During the standing long jump, participants were asked to stand on the start line and jump horizontally as far as possible and then to hold their landing position. A tape measure was then used to measure jump distance from the start line to the rear most heel of the foot upon landing. The countermovement jump used a self-selected depth in which participants were instructed to jump vertically as high as possible and to keep their legs extended while in the air. Jump height was calculated from flight time using an optical measurement system (Optojump, Microgate, Italy). The best of two attempts was recorded for both jump tests.

Strength testing

Lower limb strength was measured using a linear position transducer (Gym aware, Kinetic, Australia) to estimate the one maximum-repetition (1RM) of a deadlift exercise utilizing a velocity-based protocol provided by the manufacturer. This device has been shown to be valid and reliable method of determining a 1RM across commonly practiced resistance training exercises [149]. Participants performed a minimum of three, one-repetition lifts at maximum speed at incremental loads of 20% BM until their speed dropped to less than 0.5 meters per second (m/s). All athletes rested between 4 – 6 minutes between repetitions. Pilot testing was used to determine a starting baseline weight of each participant.

Sprint testing

Acceleration sprint testing was assessed using a radar gun, with the set up as per the load-velocity testing except that it took place indoors in a controlled environment over 22 m. Each participant performed two trials with the fasted time recorded. The same software provided by the radar device manufacturer used during load-velocity testing was used to collect raw velocity data during each sprint, which was subsequently fitted with an exponential function with its maximal velocity (Vmax) extracted. Instantaneous velocity was derived to calculate net horizontal force and maximum power (Pmax). Each linear force-velocity relationship was then extrapolated to calculate theoretical maximum horizontal force (F_0). This method has been shown to be a reliable field method to assess force-velocity profiles during over ground sprinting [22]. Sprint force-velocity profiles were then constructed using custom-made LabVIEW software. All pre- and post-intervention tests were preceded by a minimum of 72 hours to ensure athletes were not fatigued prior to testing. Pre-testing was also preceded by a familiarization period of two weeks low intensity resistance training and familiarisation of sled pushing. Post training was preceded by a one-week taper to ensure no overreaching occurred.

6.2.3 Training intervention

Participants were initially matched by speed and randomly allocated between four training groups: one unresisted and three resisted groups. A compliance threshold of 85% (14/16 training sessions) was set to be included in the study, leading to slightly uneven group sizes; unresisted n=12, light =15, moderate n=14 and heavy n=12, with loads corresponding to a Vdec of 0, 25, 50 and 75% of Vmax, respectively. The training intervention consisted of two resisted sprint sessions immediately followed by a strength session in the weight room plus two sport practice sessions on separate days per week. All athletes were asked to abstain from high intensity activity for the 24 hours prior to each sled push training session. Both resisted sprint and strength training protocols followed a linear periodization model, which involved a standard 3:1 mesocycle arrangement (i.e. three weeks of increasing intensity followed by one week of reduced workload) being completed for two consecutive four-week mesocycles. With the exception of their sport practice and specific sled loading using during the sprint training sessions, all groups preformed identical strength training programs consisting of compound multi-joint exercises for repetitions ranging between 5-10. Specific sets and repetitions for resisted sprinting are provided in Table 6.1.

Table 6.1. Sets, reps and weekly total distances for unresisted, speed-strength, power or strength-speed groups.

Week	Reps p/w	Distance per rep (m)	Total distance p/w	Reps p/w	Distance per rep (m)	Total distance p/w	Reps p/w	Distance per rep (m)	Total distance p/w	Reps p/w	Distance per rep (m)	Total distance p/w	Rest per rep (mins)
1	6	30	360	6	22.5	270	6	15	180	6	7.5	90	3
2	7	30	420	7	22.5	315	7	15	210	7	7.5	105	3
3	8	30	640	8	22.5	360	8	15	240	8	7.5	120	3
4	6	30	360	6	22.5	270	6	15	180	6	7.5	90	3
5	7	30	420	7	22.5	315	7	15	210	7	7.5	105	3
6	8	30	480	8	22.5	360	8	15	240	8	7.5	120	3
7	9	30	540	9	22.5	405	9	15	270	9	7.5	135	3
8	7	30	420	7	22.5	315	7	15	210	7	7.5	105	3

p/w =per week, m=meters, mins= minute

The sled load and sprint distance remained constant for each subject throughout the training intervention. Total work was equated for all resisted groups to that of the unresisted control group by reducing the distance per rep by the same percentage Vdec caused by sled loading. This resulted in sprint distances of 22.5, 15 and 7.5 m for the training groups loaded to cause a Vdec of 25, 50 and 75%, and meant that sprint efforts lasted approximately the same duration across participants in all training groups. All participants had three minutes rest between maximal sprint efforts.

Prior to each training session all participants performed a standardized 10-minute dynamic warm-up, inclusive of submaximal repetitions of sprinting and dynamic mobilization and activation exercises targeting the main muscle groups of the upper and lower extremities. Upon completion of the warm-up all athletes performed sprint training specific to their training group.

6.2.4 Statistical Analysis

Descriptive statistics (mean ± SD) and effect size statistics are reported for all dependent variables of jump and sprinting performance. Levene's test was used to ensure the data met the criteria for normality and homogeneity of variance. A 4 x 2 (group x time) repeated-measured ANOVA with Bonferroni post hoc comparisons was used to determine the within and between-group effects for each dependent variable as well as examining interaction effects. An alpha level of $p < 0.05$ was used to indicate statistical significance. Effect sizes (Cohen's *d*) were used to quantify the magnitude of the performance change in each group, with values of 0.20, 0.60 and 1.20 representing the qualitative thresholds for trivial, small, moderate and large effects, respectively [128]. For between-group comparisons the change score from one loading intervention was subtracted from the change score in a different loading intervention and the difference divided by the pooled standard deviation of both groups' pre-intervention.

6.3 Results

Means ± SD and magnitude of within group changes for all variables, in all conditions pre and post intervention are shown in Table 6.2. For all variables there were no significant differences between groups at baseline ($p > 0.05$). Table 6.2 shows that there were main effects of time for 0 – 5, 0 – 10, 0 – 15 and 0 – 20 m splits ($p < 0.05$), all force-velocity variables ($p < 0.05$) and the standing long jump ($p < 0.05$). There were clear trends for different responses across the groups when assessing the within-group changes. In terms of the jumps and lower body strength there were no significant changes observed with effect sizes ranging between trivial to small ($d = 0.00 – 0.34$).

All resisted interventions demonstrated significant within group improvements for 0 – 5, 0 -10, 0 – 15 and 0 – 20 m sprint times ($p < 0.05$). Within-group training effects across 5, 10, 15 and 20 m sprint times were trivial to small for unresisted sprint training, small to moderate for light and moderate resisted training and moderate with heavy training (Table 6.2). The heavy group was the only group to significantly improve 5 - 10 m. No significant improvement occurred in any group from 10 - 15 m or 15 - 20 m. Within all resisted groups, improvements in split times beyond the initial 5 m acceleration phase diminished (see Table 6.2). When comparing the change in performance between interventions there were trivial differences between unresisted and resisted loads over the first 5 m (all $d < 0.20$). However, over 10, 15 and 20 m there were small effects ($d = 0.20$-0.55) in favour of all resisted modes of training compared to unresisted training, while differences between change scores for all resisted loads were trivial (all $d < 0.20$). However, over the 5-10 m split heavy resisted sprinting provided a moderate beneficial effect compared to unresisted training ($d = 0.60$) and a small effect compared to light ($d = 0.44$) and moderate resisted training ($d = 0.33$).

Similarly, heavy resisted training provided a moderate positive effect compared to unresisted (d = 0.85) and small positive effect compared to light (d = 0.22) and moderate (d = 0.25) resisted training over 15-20 m.

With regards to force-velocity profiling across four intervention groups, Vmax, F_0 and Pmax all showed main effects between pre- and post-test. There were small but non-significant within-group differences post intervention, but differences approached significance for the heavy group for both F_0 and Pmax ($p < 0.07$). Within group comparisons demonstrated trivial to small effect size changes for F_0 and Pmax (Table 6.2). However, when directly comparing training effects between-groups heavy resisted training provided small positive effects above all other forms of training for Fmax (*d* = 20-0.33), and small positive effects for Pmax when compared to unresisted (*d* = 0.34) and moderated resisted training (*d* = 0.30). An illustration of the change in velocity over distance and force-velocity profile from pre- and post-training in each group can be observed in figure 6.1.

Table 6.2. Means ± SD for all measured variables pre-to-post intervention in young athletes completing eight weeks of either unresisted, light, moderate or heavy resisted sprint training.

	Unresisted			Light			Moderate			Heavy		
	Pre	**Post**	**ES**	**Pre**	**Post**	**ES**	**Pre**	**Post**	**ES**	**Pre**	**Post**	**ES**
VJ (cm)	41.8 ± 6.8	41.8 ± 5.0	0.00	41.4 ± 5.5	43.0 ± 6.3	0.30	43.5 ± 6.55	42.4 ± 5.8	0.17	42.9 ± 5.7	44.2 ± 6.0	0.21
SLJ (cm)[a]	213 ± 24	215 ± 22	0.10	212 ± 25	222 ± 23	0.10	221 ± 24	225 ± 22	0.08	222 ± 19	228 ± 17	0.34
Hex Bar DL (kg)	134 ± 26	137 ± 25	0.11	151 ± 22	155 ± 29	0.10	149 ± 36	152 ± 31	0.08	141 ± 24	143 ± 24	0.07
0 - 5 m (s)[a]	1.62 ± 0.13	1.57 ± 0.10	0.40	1.66 ± 0.09	1.60 ± 0.13*	0.67	1.58 ± 0.08	1.52 ± 0.10*	0.74	1.58 ± 0.07	1.52 ± 0.07*	0.84
0 - 10 m (s)[a]	2.41 ± 0.16	2.37 ± 0.14	0.28	2.47 ± 0.12	2.39 ± 0.15*	0.60	2.38 ± 0.15	2.31 ± 0.13*	0.47	2.39 ± 0.09	2.30 ± 0.08**	1.05
0 - 15 m (s)[a]	3.11 ± 0.19	3.08 ± 0.17	0.18	3.20 ± 0.17	3.11 ± 0.19**	0.54	3.09 ± 0.20	3.01 ± 0.16*	0.42	3.09 ± 0.09	2.99 ± 0.09**	1.16
0 - 20 m (s)[a]	3.77 ± 0.21	3.75 ± 0.21	0.09	3.88 ± 0.21	3.79 ± 0.23*	0.47	3.76 ± 0.23	3.68 ± 0.19*	0.34	3.76 ± 0.10	3.65 ± 0.09**	1.03
5 - 10 m (s)	0.80 ± 0.05	0.80 ± 0.05	0.13	0.81 ± 0.04	0.80 ± 0.05	0.38	0.81 ± 0.07	0.80 ± 0.05	0.15	0.82 ± 0.05	0.79 ± 0.03*	0.57
10 - 15 m (s)	0.70 ± 0.04	0.71 ± 0.03	0.32	0.73 ± 0.05	0.71 ± 0.04	0.34	0.71 ± 0.06	0.70 ± 0.04	0.24	0.70 ± 0.03	0.69 ± 0.02	0.32
15 - 20 m (s)	0.66 ± 0.03	0.68 ± 0.04	0.43	0.68 ± 0.05	0.68 ± 0.04	0.08	0.67 ± 0.04	0.67 ± 0.03	0.06	0.67 ± 0.04	0.66 ± 0.02	0.24
F_0 (N/kg)[a]	5.9 ± 1.3	6.2± 1.1	0.26	5.4 ± 1.0	5.8 ± 1.7	0.37	5.9 ± 0.8	6.2 ± 0.8	0.39	5.7 ± 1.0	6.3 ± 0.9	0.50
Vmax (m/s) [a]	8.50 ± 0.58	8.24 ± 0.57	0.46	8.10 ± 0.91	8.14 ± 0.70	0.04	8.35 ± 0.76	8.16 ± 0.47	0.25	8.31 ± 0.61	8.24 ± 0.40	0.11
Pmax (w/kg)[a]	12.9 ± 2.7	13.2± 2.5	0.12	11.5 ± 2.9	12.3 ± 4.0	0.27	12.6 ± 2.0	13.1 ± 1.8	0.19	12.2 ± 2.0	13.3 ± 1.8	0.51

VJ =vertical jump, SLJ = standing long jump, CT = Contact time, FT = Flight time, F = maximal theoretical force, Vmax =maximal theoretical velocity, Pmax = maximal theoretical power

[a]Significant main effect of time ($p < 0.05$)

*Significant within group difference pre-to-post intervention ($p < 0.05$)

**Significant within group difference pre-to-post intervention ($p < 0.01$)

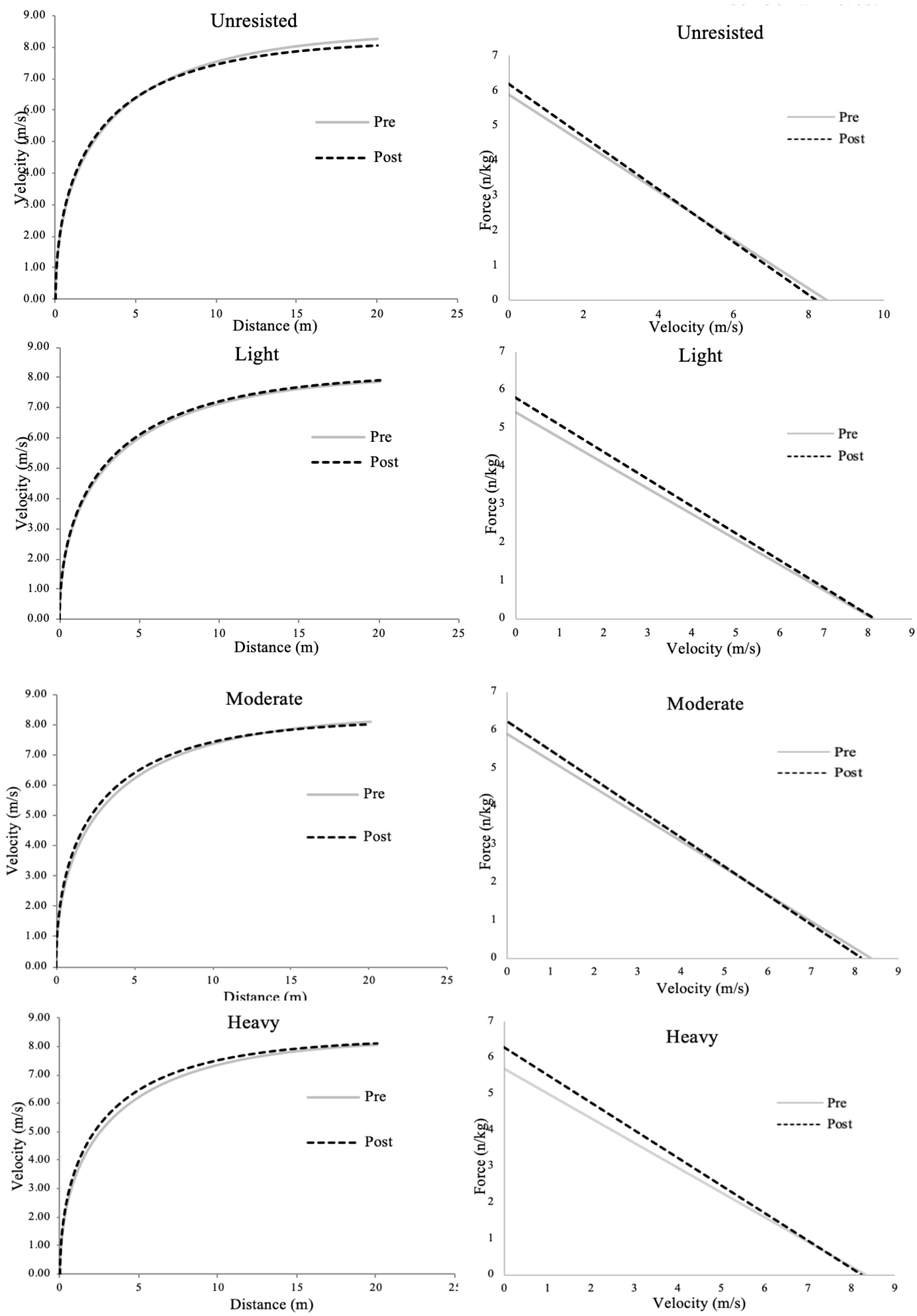


Figure 6.1. Pre to post changes in velocity-distance and force-velocity profiles after an 8-week sled push training intervention at unresisted, light, moderate and heavy loads.

6.4 Discussion

The aim of the study was to assess the effectiveness of unresisted and resisted sled-push training on short distance sprint performance at multiple loads reflective of speed-strength, power and strength-speed zones of training. The main findings of the present study were that resisted sprinting was more effective than unresisted sprinting in improving short distance sprint performance, and that heavy loads seem to provide the greater benefits of increasing acceleration, force and power. It seems that young athletes respond to resisted sled pushing across a range of loads. However, between-group effects suggest resisted sled pushing at a heavy load in a strength-speed training zone may elicit enhanced acceleration performance and increased force and power production in comparison to training with lighter or unresisted loads.

Sled push training being categorized as a sprint specific horizontal strength training exercise provided minimal transfer to both vertical and horizontal jump performance and lower body strength. The non-significant and trivial to small magnitude of change within groups supports previous research that training is movement specific [129]. A small effect size change was observed in the heavy group during the standing long jump and the light group during the vertical jump. Due to the reduced sprint distances as load increased within each intervention group the lightest resisted group and heaviest resisted would have spent more time applying force vertically and horizontally respectively [136].

The availability of research on resisted sled push training in comparison to resisted sled pull training reinforces the need for more intervention studies to determine the effectiveness of sled pushing as a sprint specific method of training. transfer to both vertical and horizontal jump performance and lower body strength. The non-significant and trivial to small magnitude of change within groups supports previous research that training is movement specific [130]. It is important to note however, the loads previously studied and categorised as “heavy” (20 %BM) within a youth population would still be considered light in comparison to the loads used in this study [130]. All resisted-sprint groups had small to moderate significant within group improvements in sprint times. The magnitude of effect was greatest over the initial 5 m and increased with greater loading. This indicates that resisted sprinting affected the initial acceleration phase, particularly in the heavy group. Decreases in split times beyond the initial 5 m were primarily a result of the improvement within the acceleration phase. However, the heavy group was the only group to significantly improve between the 5 - 10 m split, suggesting sled pushing at heavy loads may have additional benefits outside the initial acceleration phase, providing the necessary force dominant stimulus to elicit the desired training response in young athletes. However, more research is needed examining the acute kinetics and kinematics of sled pushing to quantify the mechanical determinants of these changes.

There were significant main effects of time on the force-velocity profiles but no significant changes at a group level. However small changes that approached significance ($p < 0.07$) in F_0 and Pmax were observed in the heavy group ($d = 0.50 – 0.51$), while the heavy group also experienced small positive effects above and beyond other training groups when comparing the change in F_0 and Pmax. These findings illustrate that the adaptations occurring from resisted loads seem to be specific to the imposed demands, with the heavy loads appearing to favour horizontal force and power adaptation. The fact Vmax decreased for most groups also supports the notion of training specificity, with most groups working against resistance and below maximal speed. The lack of any improvement in Vmax in the unresisted group may reflect the fact that sprinting is a habitual activity in young athletes, and that the training programme did not provide a stimulus to elicit performance improvements. The findings may also be specific to the population studied. Previous meta-analyses have shown that with traditional resistance training young athletes respond most to work at higher intensities and that post-pubertal athletes make greater strength gains than pre-pubertal populations following resistance training [110,137]. If sled pushing is considered a specialised form of horizontal resistance training then heavy loads, representing a high-intensity of work, may be particularly useful for young athletes who are post-PHV to increase their sprint force, power and velocity.

6 .5 Perspective

The aim of the present study was to assess the effectiveness of unresisted and resisted sled-push training at light, moderate and heavy loads in high school athletes. All resisted groups made significant, positive improvements, suggesting a range of loads can be effective in improving the sprint performance of young athletes. However, when comparing effects between intervention groups there was a clear trend for greater improvements in sprinting force, power and performance over short distances when training with a heavy sled load. Cumulatively, the results of this study show that post PHV males within limited training exposure to resisted sprinting may reap the greatest gains in acceleration performance with a heavier external resistance which is representative of a strength-speed training zone. Given the constant desire to individualise training, future research should examine whether greater gains in performance can be achieved if resisted push-load is prescribed based on individual weaknesses in the force-velocity profile.

CHAPTER 7. RESISTED SLED TRAINING FOR YOUNG ATHLETES: WHEN TO PUSH AND PULL

This chapter comprises of the following paper currently under review:

Cahill MJ, Oliver JL, Lloyd RS, Cronin JB, Clark KP, Cross MR. Resisted Sled Training for Young Athletes: When to Push and Pull. *Strength & Cond. J* (Under Review).

7.0 Prelude

This chapter is an attempt to draw the learnings of the thesis together into an evidence-based practice approach to the programming of RST pulling and pushing. This chapter considered the gaps, limitations and recommended methods first presented within the literature review in Chapter 2. It also includes the empirical evidence gathered throughout the four acute and longitudinal chapters. This evidence combined with a liberal dose of practical experience and observations of the principle researcher, is used to provide updated practical applied guidelines on best practices for coaches to integrate resisted sled training into their preparatory phase of training. This chapter acts as the practical application section of the thesis and extends beyond meso-cycles of training to present an integrated, periodised resisted sled training plan for the preparatory phase of a season that can be adapted to suit the needs of the sport, coach and athlete.

7.1 Introduction

The development of sprint speed is a pivotal characteristic required for most sporting success in young athletes [53]. Increases in speed have been shown to be non-linear in young athletes due to the development of the central nervous system pre-peak height velocity (PHV) and the increases in hormone levels at the onset of puberty during mid/post-PHV [12,138]. Therefore, it has been suggested that training modalities should mirror the interaction between growth, maturation and speed development, with training for pre-

PHV emphasising neural adaptation and post-PHV emphasising neural and morphological adaptation[139]. The interaction of age, growth and maturity can also influence the development of the subsequent phases of sprint performance[8,140]. Sprint speed training for young athletes can be broken into both non-specific (e.g. traditional resistance training) and specific (e.g. resisted and assisted) modalities, with the latter being suggested as potentially more suitable for post-PHV athletes due to the structural and hormonal changes that occur at the onset of puberty [15,39].

A common form of sprint specific training is to add a resistive load to movement in a horizontal plane of motion, known as resisted sprinting [48]. Although many forms of resisted sprinting exist, one of the most common methods is resisted sled training (RST). Two popular forms of RST are sled pulling and pushing as illustrated in Figure 7.1, both of which have been suggested as effective ways to improve sprint performance [48]. Manipulating the load in RST has been suggested to target different phases of the sprint. Training with heavy and light loads has been shown to improve the acceleration and transition to maximum velocity phases respectively [50]. However, it is important that practitioners familiarise young athletes with any type of novel training method first. Therefore, practitioners need to ensure that the method of RST, the loading parameters used and the specific phase of sprinting being targeted are appropriate for the population being trained. Therefore, the aim of this article is to provide practitioners and coaches with insight into how to best integrate RST during the preparatory phases of training within a periodised training plan to maximise gains in sprint performance in young athletes.

Figure 7.1. A young athlete performing resisted sled pulling (A) and pushing (B).

7.2 To Push or to Pull?

Although both sled pulling and pushing provide resistance to sprinting, key differences exist that alter the kinematics of the movement; most noticeably, the base weight of the sled, its anterior position and the use of the arms. Pushing removes the natural action of the arms during sprinting, therefore it is not considered as a method where overload is coupled to maintaining sprint mechanics. However, in terms of body position and lower body sprint mechanics with additional load, similarities exist that could positively affect the kinetics of sprinting. One such similarity is the increased forward lean during both types of heavy RST. Although this will undoubtedly affect sprint mechanics and cause a degradation in technique, young athletes may in turn improve the orientation of the foot strike leading to more desired application of horizontal force when accelerating [47,48,101]. However as illustrated Figure 7.2, when young athletes are *pushing* moderate and light loads in which there can be noticeable decline in postural control and negative angle of forward lean (circled in red). This is most likely due a combination of a lack of whole-body/core strength in young athletes to maintain a straight line from ankle to shoulder and there not being enough anterior load to support the outstretched arms and body during sled pushing at higher velocities. Conversely, during sled *pulling* the arms provide additional balance during cyclical running motion and the posterior loading of the sled and waist belt provide a counterbalance effect to cue the hips into extension.

Figure 7.2. A group of post-PHV athletes sled pushing at an individualized Vdec across different zones of training.

7.3 Prescription of Load

Early research in RST has used absolute load or percentage of body mass (%BM) to prescribe sled load, however many limitations have been identified in both adult and youth populations [49,135]. Notably, when load is prescribed in terms of %BM to young athletes of varying levels of maturation, strength and training history, a high degree of variability exists both acutely and longitudinally in response to training [39,68,123,135]. When performing resisted sled pulling at the same load as a %BM, it has been shown to slow pre-PHV athletes by 50% more than post-PHV athletes [39,68], with post-PHV athletes more responsive to RST[7]. Furthermore, recent work has also confirmed that working at a given %BM would lead to large variability between adolescent athletes in the amount they are slowed during both sled pulling [123] and pushing [135]. Therefore, prescribing training as a given %BM is likely to cause different levels of stress and training adaptations across individual young athletes and is not an ideal way to prescribe load. The degree of between-athlete variation is higher in sled pushing; the variability in the load to cause a given decrement in velocity (Vdec) has been shown to be almost double between those who tolerate load the least to those who tolerate the load the most, a finding that was consistent across multiple loads and zones of training [135].

Currently, little is known about the individual factors that determine the ability of young athletes to tolerate load during RST. The linear relationship of force-velocity (FV) and load-velocity (LV) has been established by Cross *et al.* [100,141] in sled pulling for adults and later confirmed by Cahill *et al.* in young athletes for pulling [123,135] and pushing [12]. The linear load-velocity relationship can be used to describe the degree to which increasing load causes a Vdec during sprinting. Training can then be prescribed with an individualized load that causes a given amount of Vdec. The use of Vdec has been suggested as a reliable method of sled load prescription to maintain a consistent training stimulus in RST across a range of young athletes in both pushing and pulling[100,123,135]. The Vdec approach allows coaches and practitioners to individually prescribe individual sled loads and zones of training to each individual athlete. Given the maturational differences across young athletes, and the differences in sled types and surfaces, coaches can individualize a given load for each athlete to better target the desired training adaptation. Although this method allows for qualitative prescription of load across a group, it does require a LV profile to be created for each athlete. Calculating maximal velocity during one unresisted and at least two resisted sprint trials either side of 50% Vdec via laser or radar is recommended [100]. However, if this technology is not available to practitioners, the highest average velocity across 5 m splits using timing gates can be used to recreate a LV profile also. Advances in handheld cameras have allowed for mobile applications such as the My Sprint App to reliably calculate sprint performance, specifically the FV profile of unresisted sprints[92]. It is also worth noting that the Vdec method could only be used to prescribe load in the conditions in which the LV relationship was established (e.g. testing and training on the same type of surface). Traditional resistance training would never be prescribed as a set %BM for all athletes and thus intuitively the same logic should also apply to RST. For example, to prescribe training load for the back squat a practitioner could establish a young athlete's 1RM by gradually testing the athlete across increasing loads to then prescribe a training load relative to 1RM. In the same way practitioners should test young athletes' ability to manage load in RST by testing them across a range of loads and using the LV relationship to prescribe training load. An illustration of the between-athlete variability in load to cause a given Vdec for both sled pushing and pulling is shown in Table 7.1.

Table 7.1. The loads required to slow three athletes by 50% Vdec for both sled pushing and pulling.

		Vmax (m/s)	*Sled Pushing (%BM)*	*Sled Pulling (%BM)*
Athlete 1	50% Vdec	4.0	78	101
Athlete 2	50% Vdec	3.6	69	91
Athlete 3	50% Vdec	3.7	55	77

7.4. Heavy, Moderate or Light Loads?

Recent research [123,135] has identified different zones of training in RST using the Vdec method; strength-speed, power and speed-strength with an additional zone of training for sled pulling known as technical competency. A Vdec of <10% corresponding to the technical competency zone of sprinting can be used by coaches intending on adding resistance without effecting sprint mechanics. Loads that cause a Vdec >10% RST have been suggested as a specialized mode of horizontal resistance training in both sled pushing and pulling for young athletes [123,135]. An example of a linear RST progression is illustrated in Figure 7.3, which when observing the figure from left to right, shows an emphasis on increasing intensity (external load/Vdec) while decreasing the technical specificity of maximal velocity sprinting. Both sled pulling and pushing can be implemented as horizontal resistance training exercises across the LV profile. However, the desired adaptation is dependent on the coaching emphasis within training zones of strength-speed (green zone), power (yellow zone), speed-strength (red zone) with the exception of the technical competency zone (blue zone).

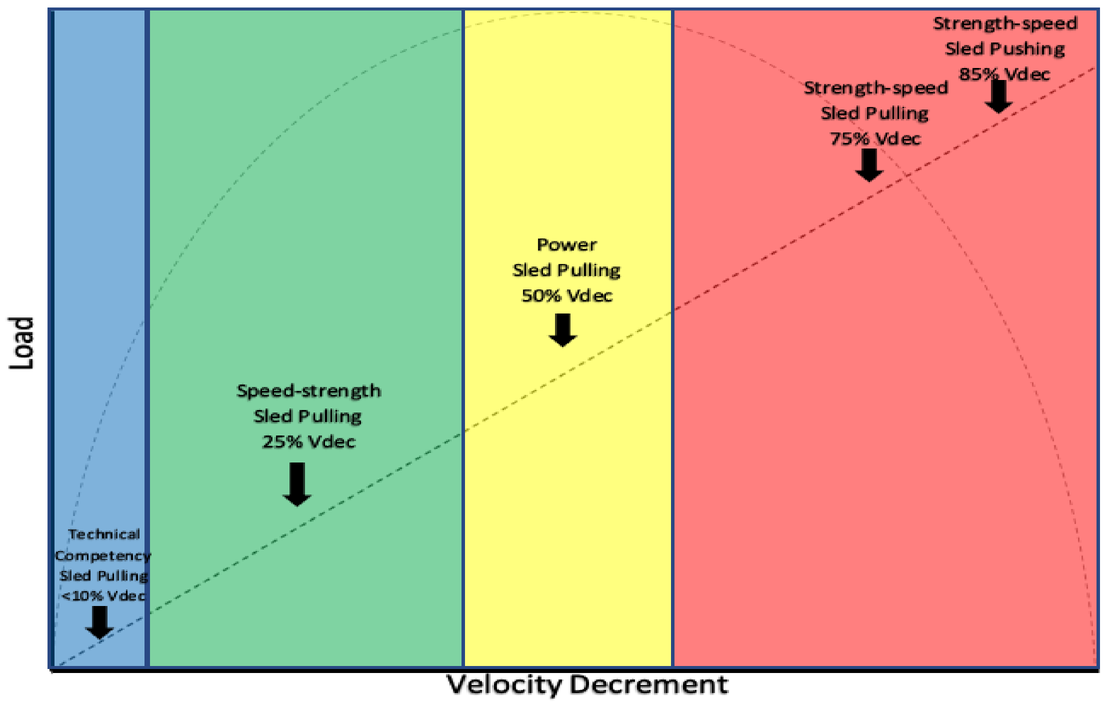


Figure 7.3. Load velocity profile with respect to horizontal resistance training.

Research reviewing all acute and chronic literature on RST loading parameters has suggested heavier loads are more effective than lighter loads during the early phase of acceleration, whilst moderate to light loads will improve the late acceleration and transition to maximum velocity phases of the sprint respectively [48,50]. Therefore, different loads and zones of training should be employed during RST to improve the specific phases of the sprint. Although RST is a sprint specific mode of training for young athletes, training age, competency, maturation and strength should always be considered to ensure the selection of appropriate exercises. A cumulative level of baseline traditional strength training is recommended before introducing young athletes to a structured RST program and progressing from light to heavier loading schemes. However, heavier loads can be used with young athletes to emphasize certain aspects of proper sprint mechanics through specific positions holds and marches at lower speeds. Heavier loading parameters may be utilized more quickly for more mature competent young athletes (mid/post-PHV) due to their natural ability to develop higher relative horizontal forces as maturity and strength increase [54,142].

7.5 Targeted Adaptation

Young athletes with a lower training competency to maintain good mechanics during RST should be introduced progressively through gradual increased intensity (external load/Vdec); although coaches should be aware of how the load effects the postural mechanics during RST to ensure the desired adaptation is achieved. However, due to the overall increase in mass and strength gains in post-PHV youth, this population may adapt more quickly to heavier loads compared to pre-PHV. Although limited research exists around RST for pre-PHV athletes, it has been shown that sled pulling is more beneficial for mid/post-PHV athletes [39]. A recent meta-analysis on the variation in response to sprint training by Moran *et al.* [143] recommended pre-PHV athletes should focus on gross fundamental movement patterns and activities that enhance stride frequency. Therefore, RST should be viewed as a horizontal resistance training exercise with the aim to improve capacities to produce force during sprinting, specifically during post-PHV athletes. Although even the most competent pre-PHV athletes with a high training age may not experience the same rate of adaptation to produce force during RST at heavier loads due to maturational differences that occur during puberty.

The progressive specificity of the exercises to improve force producing capacity in both sled pushing and pulling across the four zones of training is illustrated in Figure 7.4. Additionally, the maturational bias to training responsiveness is also included in the figure. The purpose of the technical competency zone of training is to minimally disrupt sprint mechanics. Due to the use of the arms and base weight of most push sleds, this zone does not apply to sled pushing. The technical competency zone of training might be used more by track coaches to add resistance at certain times of the year while maintaining technical sprint mechanics. However, sports and positions such as linemen in American Football or racquet sports may never use this zone of training given the specificity of the sport and playing positions. The speed-strength zone of training can be used in both forms of RST to target the transition to Vmax phase of sprinting. It can also be used as a developmental strength phase to introduce RST to young athletes, specifically less mature or less competent athletes. Specific areas of sprint mechanics can be emphasized during both forms of RST. Specific areas of sprint mechanics can be emphasized during both forms of RST at various loads. Practitioners can incorporate drills to coach areas such as the forward lean, proper postural control and knee drive. Emphasis on such areas could be particularly useful for pre-PHV athletes as sprinting technique should be a focus point due to neural adaptation preferences [139]. However, the development of whole body strength training in both planes should not be neglected to further assist postural control. Developmental and introductory loads within the technical competency and speed-strength zones are recommended to be incorporated in pre-PHV athletes strength programs as a baseline modality of horizontal strength exposure and development before heavier loads are implemented. This multi-modal developmental approach to training can provide a platform for pre-PHV athletes to advance to more complex tasks and specialized strength variations at higher intensities [110,134,138].

The purpose of the power and strength-speed zones of training are to emphasize maximizing power and rate of force development respectively. Both zones of training can be used in RST to target the acceleration phase of sprinting. During heavy sled pushing, young athletes are better able to maintain hip position, postural control and lower limb alignment as compared to pulling heavy loads [48], but without an arm drive this training mode renders sled pushing less specific to sprinting in comparison to sled pulling. Therefore, sled pushing may be favoured as a form of very heavy RST over sled pulling initially during the early preparatory phase to increase total body horizontal strength. During sled pulling the waist belt can act as an external coaching cue to push the hips into extension; however excessive loading may lead to a break in the hips causing a less optimal body lean angle which negatively effects the orientation of the foot strike.

Targeted Adaptation	Technical competency *<10% Vdec*	Speed-strength *25% Vdec*	Power *50% Vdec*	Strength-speed *75 - 85% Vdec*
	Add a resistive stimulus without affecting mechanics	Increase force production capability during transition to Vmax	Increase force production capability during late acceleration	Increase force production capability during initial acceleration
	Not applicable due to use of the arms	Total body horizontal strength with transition to Vmax emphasis	Total body horizontal strength with late acceleration emphasis	Total body horizontal strength with initial acceleration emphasis
Training bias based on stage of maturity	Greater synergy between training stimulus and age-related neural development of pre-PHV youth		Greater synergy between training stimulus and maturity-related neural and structural development of post-PHV youth	

*PHV = peak height velocity

Figure 7.4. The interaction of RST with load, method, desired adaptation and maturational status in young athletes.

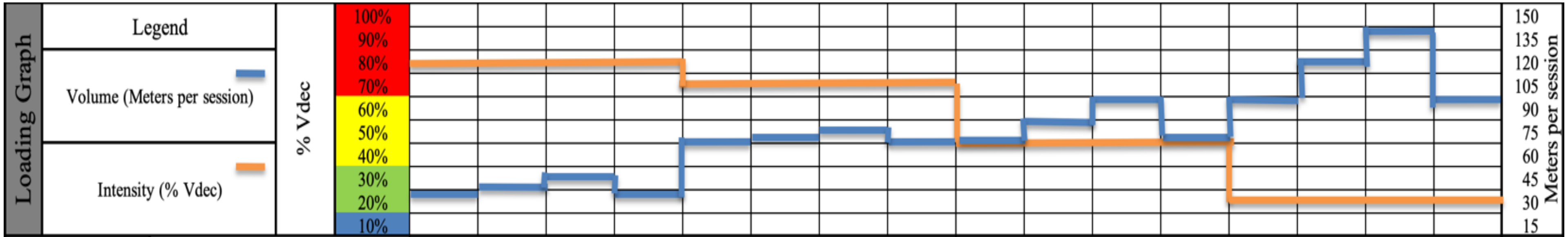
7.6 Periodized Preparatory Phase Training Plan

A periodised training plan specific to monitoring the workload of RST is not recommended for pre-PHV athletes as it consists of a high structure with less emphasis on gross motor patterns [144,145]. Pre-PHV athletes should be exposed to a low structured and multi-dimensional training approach, delivered in an exploratory style environment during early childhood [146]. An example of a more targeted, highly structure periodised preparatory phase training plan is provided in Figure 7.5. This training plan is designed for post-PHV high school team sport athletes aiming to improve overall short distance sprint performance. The periodised plan should be considered within the context of an overall training program, which would naturally integrate other important training qualities such as strength, agility with technical and tactical practice. The training plan is offered as an example program and practitioners should adapt their program based on the needs of the athlete, demands of the sport and constraints of the athlete's environment (equipment, time, etc). For example, the training plan could be shortened to an 8 or 12-week plan by either shortening the blocks to 2-3 weeks or removing a specific phase that might not apply to the given sport (i.e. transition to maximum velocity (Vmax) phase in baseball or basketball).

A linear periodised model of training is recommended for those with a lower training age, such as inexperienced, pre-PHV athletes, to allow for ample recovery and adaptation to the desired stimulus[147]. It is generally recommended to progress from a general preparation phase (GPP) to more specific preparation phase (SPP) during an annual training plan,[147] with greater time spent in GPP for less experienced and less mature individuals. Figure 5 shows a traditional linear periodization model consisting of three weeks of increasing volume (meters per session) followed by a one-week de-load. The increased volume is prescribed in accordance with a progressive decrease in loading intensity (Vdec). Both intensity and volume are linked to different phases of training, targeted phases of sprinting, and methods of RST to improve the kinematics and kinetics of sprinting. Heavier loading schemes for RST can be used in earlier preparatory phases (e.g. strength-speed) to emphasise developing maximum strength capabilities in a horizontal plane of motion.

During the latter specific phases (e.g. speed-strength) as competition approaches, faster running speeds at a reduced loading intensity can be used to develop and maintain power and explosive sprinting capabilities. The reduction in overall training load is designed to positively affect the athlete's performance entering a competitive or priority phase.

During the competitive phase, coaches are recommended to continue to incorporate RST to ensure exposure to horizontal strength training throughout the season. Moderate loads within the power zone of training are recommended to be utilized in-season; however, coaches must consider multiple factors such as the fixture calendar, time, resources and athlete fatigue monitoring, which are all likely to influence the loads that optimize power output.



		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Training Cycle	Macro	GPP								SPP							
	Meso	1				2				3				4			
	Micro	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Load	Training Frequency	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	Reps per Session	7 x 5m	8 x 5m	9 x 5m	7 x 7.5m	6 x 7.5m	7 x 7.5m	8 x 7.5m	6 x 7.5m	4 x 15m	5 x 15m	6 x 15m	4 x 15m	4 x 22.5m	5 x 22.5m	6 x 22.5m	4 x 22.5m
	Session Training Load (Volume x Intensity)	2975	3400	3825	2975	3375	3938	4500	3375	3000	3750	4500	3000	2250	2812	3375	2250
Training Emphasis	Zone of Training	Strength-Speed				Strength-Speed				Power				Speed-Strength			
	Targeted Phase of Sprinting	Acceleration				Early Acceleration				Late Accleration/Transition				Transition to Vmax			
	Resisted Sled Method	Sled Pushing				Sled Pulling				Sled Pulling				Sled Pulling			
	Coaching Mechanics Emphasis and Cueing	Posture Total Body Lean				Lower Body Knee Drive				Hip Extention				High Knee Snap			
		"Straight line from ankle to head"				"Push the ground away/piston like action"				"Belt buckle to the sky"				"Step over your knee/cycle like action"			

% Vdec = percentage of velocity decrement from maximal sprint; GPP = General preparation phase; SPP = Specific preparation phase; Vmax = Maximum velocity.

Figure 7.5. A periodised preparatory phase training plan integrating resisted sled training for post PHV young athletes for sprint specific performance improvements.

7.6.1 General preparation phase training guidelines

The focus of training within a zone of strength-speed should be to increase the rate of force development (RFD) and power while maintaining or potentially increasing strength levels[148]. This is achieved by moving relatively heavy loads as fast as possible to enhance RFD capabilities. Recent research examining sled loading at heavier loads suggests a targeted improvement within the early acceleration phase[48,50]. Heavier loads during RST have been shown to increase horizontal force application and improve the initial acceleration to a larger degree when compared to lighter and unresisted loads[51,80]. As illustrated in Figure 5, heavier loads (greater % Vdec) pushed and pulled for higher rep ranges at shorter distances (5 and 7.5 m) are used in the general preparation phase in comparison to the specific preparation phase. Training at such heavy loads for short distances is designed to increase the initial and early acceleration phase of the sprint without causing unnecessary fatigue (time under tension). From GPP 1 to GPP 2 there is an increasing overall training load to ensure a higher accumulation of volume and intensity is achieved during the preparation phase. With reference to Figure 3 and 5, both sled pushing and pulling are recommended. However, due to the use of the arms, sled pushing may be viewed as a more whole-body horizontal resistance training exercise and a less specific movement associated with the mechanics of sprinting. Therefore, it is recommended that heavy sled push is used prior to heavy sled pulling in the general preparation phase of training within the strength-speed zone. However, sled pushing may be favoured over sled pulling for prolonged periods for specific sports and positions, such as offensive or defensive linemen in American Football.

7.6.2 Specific preparation phase training guidelines

The focus of training within a zone of power is to optimize adaptation to maximal power (P_{max}). Practitioners can determine the optimal sled load to maximize power production due to the linear relationships between force-velocity and load-velocity during sled pulling and pushing in young athletes[123,135]. The load that causes a Vdec of 50% therefore optimizes power production due to the parabolic relationship between power and velocity[49]. However, even though it is considered the optimal load for RST that maximizes power production, it does not necessarily ensure optimal gains in short distance performance. Just like any exercise selected, it is task-specific and dependent on the individual FV characteristics of the athlete [107]. The power zone of training is recommended within the continuum of decreasing intensity and increasing sprinting specificity to target the late acceleration phase of training. The focus of training within a speed-strength zone should be to produce peak adaptations in RFD before competition[148]. The prior phase of training at a greater intensity (%Vdec) creates a sustainable platform for athletes to progress to enhancing their task-specific speed-strength[148]. Research examining sled loading at lighter loads suggests a targeted improvement in the transition to Vmax phase[48,50]. As illustrated in Figure 4, moderate to lighter loads (reduced % Vdec) pulled for lower repetition ranges across higher distances (15 and 22.5 m) are used in the SPP in comparison to the GPP. Training at light to moderate loads for longer distances is designed to increase the late acceleration and transition to Vmax phase of the sprint. From specific preparation phase 1 to specific preparation phase 2 there is a decreasing overall training load to ensure accumulation of volume and intensity does not induce any residual fatigue in the young athlete as the competition phase nears. With reference to Figure 2 and 4, sled pulling is recommended over sled pushing during this phase. Although sled pushing may lead to improvements that are similar to sled pulling when training at the same relative intensity, anecdotal observations suggest sprint mechanics are less specific with pushing, and therefore sled pushing is recommended more as a preparatory horizontal resistance training exercise. The use of the arm drive in sprinting is critical to overall sprint performance[142], and should therefore be integrated into training wherever possible the closer a young athlete gets to competition.

7.7 Training Considerations

Using the periodised preparatory plan as a guideline, coaches also need to consider how to implement RST sessions within their own environment. Prescribing individual loads to a large group of athletes can be very time intensive to set up, thus educating the athletes as to how much load they should put on the sled in advance of the session starting will maximize training time. Coaches should also consider the total number of athletes within the training session and how they can be divided into different training groups to ensure an efficient flow. For example, coaches can set a total time per athlete and group, such as; three minutes per group, allowing six athletes within a group having 30 seconds to set up (exchange waist harness or push sled) and perform each rep with a continuous 2 minutes and 30 seconds rest between repetitions. Total training time will then dictate the number of repetitions the coach is able to prescribe. Figure 6 illustrates an example of the distance set for the technical competency, speed-strength, power and strength-speed zones of training. In this example, the total distance per repetition is equated by reducing the distance per repetition by the same percentage Vdec caused by sled loading from a 30 m unresisted sprint (i.e. a reduction of 75% in Vdec would equate to a reduction of 22.5 m or 75% from 30 m). Coaches should be conscious of poor technique such as excessive rounding of the back or too much breaking in the hips during RST sessions, which could stem from induced fatigue or excessive load. Should coaches observe technical breakdown, then the load should be adjusted to mirror a more optimal angle of forward lean and the Vdec noted to ensure the coach is aware of the targeted zone of adaptation.

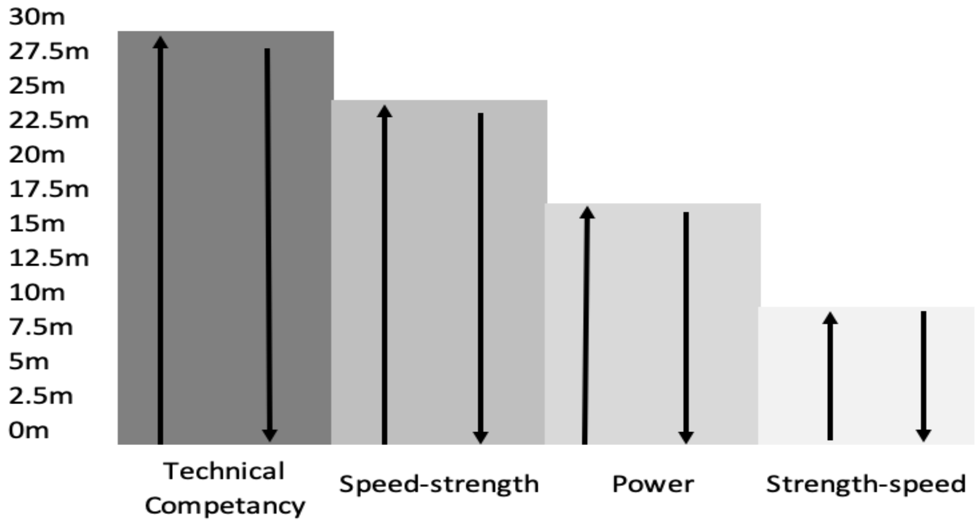


Figure 7.6. An example of a RST drill set-up for young athletes, in which work is equated across 4 different zones of training based off an unresisted 30 m sprint.

Although a linear periodization model for the preparatory phases of a high school team sport season has been outlined in this article, incorporating RST for more advanced or junior elite athletes should be integrated into more specific models of periodization such as undulating or block periodization. Coaches working with one to one or smaller groups of young athletes of a higher horizontal strength training age may require loading to be individualized to their pre-training FV characteristics with longer periods of emphasis spent within the identified area of weakness (i.e. speed-strength or strength-speed). Individually prescribing load based off force or velocity dominance may also benefit the athlete during competition and reduce the likelihood of overtraining during critical periods within a competitive calendar. However, further research is needed to determine the effectiveness of prescribing load based on an individual FV profile in young athletes, particularly over long-term training programs.

7.8 Practical Applications

- Sprint-specific training should be used to develop speed using RST in the form of both sled pushing and pulling. Coaches need to consider the maturity, competency and training age of young athletes to prescribe the most appropriate sprint-specific training programs.
- Specific areas of sprint mechanics such as forward body lean, postural control and knee drive can be emphasized within different training zones across pre, mid and post PHV to reinforce good sprint technique.
- Different zones of training can provide coaches with a targeted approach to improving specific phases within a sprint.
- During the earlier preparatory phases acceleration can be targeted through low velocity RST at higher intensities. As competition approaches coaches can target late acceleration and transition to Vmax through higher velocity RST at lower intensities.
- Sled pulling is recommended as a more specific form of RST than sled pushing due to the use of the arm drive.

CHAPTER 8. SUMMARY, FUTURE RESEARCH DIRECTIONS AND PRACTICAL APPLICATIONS

8.1 Summary

Resisted sled training is a common method of sprint specific training used by coaches across an array of sports, however, a stark contrast in the empirical evidence investigating sled pulling and pushing exists. Furthermore, prior to this thesis there was a paucity of research examining the acute and longitudinal training effects of RST across a range of loads in young athletes during a critical period of adolescence. This thesis has added to the body of knowledge by reviewing the literature in RST as it pertains to young athletes. The experimental studies were constructed with scientific rigour consisting of 160 athletes for the acute studies and 104 athletes for the training studies. The results of the acute studies provided new and impactful information to inform practitioners using RST with youth about the reliability and linearity of the Vdec approach, a novel method to prescribe load. The acute studies also provided novel research on the amount of between athlete variability in the load required to cause a given % Vdec during RST, reflecting factors that may influence the ability of athletes to sprint against load, such as strength, speed and maturation. The training studies informed practitioners of the effectiveness of RST and how different training loads influence not only split times but also the sprint force-velocity profile of young athletes, and specifically how load affects horizontal force and power.

This thesis was continually guided by the overarching question of "What are the acute and chronic training responses to resisted sled pushing and pulling in young athletes?". The basis for this overarching question was formulated by gaps identified in the literature, such as: 1) a paucity of research examining the acute and longitudinal effects of RST for both pulling and pushing in young athletes ; 2) limitations identified with current methods of load prescription (%BM); 3) no previous study had examined the reliability and linearity of the Vdec method or the between athlete variability of a given load to cause a % Vdec, in young athletes; 4) no previous study had examined how sprint force-velocity profiles are influenced by RST across multiple loads; and, 5) a lack of clear guidelines existed with regards how to integrate RST into a training plan. Consequently, addressing these gaps has provided empirical evidence and guidelines for RST in young athletes, which can be used to aid the development of short distance sprint performance, an important quality in many sports. The aim of this chapter is to summarize the main findings, outline practical applications to practitioners and provide the limitations and recommended future research directions.

8.1.1 Aim 1:

To review and compare literature related acute and chronic training responses to resisted sled pushing and pulling.

Key points to consider

- The majority of RST research has focused on resisted sled pulling in comparison to sled pushing. The acceleration phase is most researched in RST over any other phase of the sprint. Load has been expressed primarily in terms of absolute load, percentage decrement in velocity and percent body mass (%BM) with the latter being the most common. However, the Vdec method has been described as the most appropriate for prescribing sled load.
- The sled pull is consistently reported to reduce an athlete's stride length and stride frequency as load increases. Angular kinematics have also been studied during sled pulling and findings show joint angles at the hip and trunk increase compared

to unresisted sprinting. Furthermore, trunk angle forward lean has been shown to increase as sled loads increase.

- Researchers have suggested that heavier sled loads and the resultant increased forward lean could lead to an acute increase in horizontal force application while performing resisted sprints.
- Acceleration and maximum velocity adaptation may be a function of sled load. Heavier type sled load training likely improves the initial acceleration phase where high horizontal forces are required, whilst light to moderate loading will likely improve the maximal velocity phase due to low horizontal force and higher velocity requirements.
- The characteristics of an athlete may influence both the acute and chronic responses to RST. The available research suggests that maturity, sex and training history are all likely to influence the ability to tolerate load.
- Loading should be prescribed on the percentage reduction in velocity for each athlete rather than a set percentage of body mass. Reductions in velocity of <10%, <35%, 50% and >65% during resisted sprinting are suggested to reflect high-speed (technical), speed-strength, power and strength-speed stimuli.

Aim 1 conclusion

Little uniformity exists regarding assessment, load prescription and targeted adaptation for adults and young athletes undertaking RST. Resisted sled sprinting provides a stimulus for high horizontal force application and when incorporated into a strength training program it might prove to be a more effective way of improving sprint performance compared to unresisted sprinting or traditional resistance training alone. However, loads should be prescribed at a % Vdec rather than %BM to account for differences in maturity, relative strength and training history.

8.1.2 Aim 2:

To examine the reliability, linearity, between-athlete variation and usefulness of individual load-velocity profiles associated with the velocity decrement from maximal speed (Vdec) approach to prescribe training loads during sled pushing and pulling in young athletes.

Key points to consider

- Reliability and linearity
  - There was no substantial change across trials, reflecting an absence of systematic bias across all variables studied across three different testing occasions in both sled pushing and pulling.
  - The CV for all variables (Vmax, load and the slope of the load-velocity relationship) was consistently < 10% in both sled pushing and pulling.
  - The majority of ICCs were above acceptable thresholds but ranged from 0.60 to 0.92. When load was expressed in absolute load (kg), high relative reliability (ICC <0.90) was observed for both sled pushing and pulling.
  - For all subjects the load-velocity relationship in both sled pushing and pulling was highly linear (r^2 > 0.95), as was the case for the mean data across the group in each study (r^2 = 0.99).
  - The highly linear relationship between load and velocity and acceptable reliability of variables derived from individual load–velocity profiles for both sled pulling and pushing allows for consistent sled-load training prescription across training zones using the Vdec method in young athletes. Training zones identified include; technical competency (sled pulling only), speed-strength, power and strength-speed in young athletes.

- Usefulness of load-velocity profiles and the between athlete variability
    - Based on the individual load–velocity relationships in sled pulling, the load that corresponded to a Vdec of 10, 25, 50 and 75% (95% CI) were 18 (14–21), 45(36–53), 89 (71–107), and 133% (107–160) for sled pulling.
    - Based on the individual load–velocity relationships in sled pushing, the load that corresponded to a Vdec of 25, 50 and 75% (95% CI) were 33 (23-42) %BM, 66 (45-85) %BM and 100 (69-131) %BM. This suggests that when compared to pulling, pushing requires heavier loads to cause the same Vdec and that the load required is more variable across participants in pushing compared to pulling.
    - A higher degree of between athlete variation was found in sled pushing in comparison to sled pulling.
    - Given the differences in loading and variability, caution must be used when comparing sled pushing and sled pulling.
    - Push sleds are typically bigger in size, have a larger surface area and are likely to increase the athletes Vdec more due to the increased coefficient of friction between the sled base and surface from the placement of the arms onto the vertically aligned poles. The anterior and posterior orientation of the sled may also influence the activation of specific muscle groups.
    - Little is known about the individual factors that determine the ability of young athletes to tolerate load during RST, with more research needed. Further research, such as the assessment of specific measures of strength and fat-free mass, is needed to better explain the variability between athletes within a group of post-PHV.

Aim 2 conclusion

The load-velocity relationship for sled pushing and pulling in youth athletes was found to be highly linear in Chapters 3 and 4. Both the slope and Vdec approach to sled pushing and pulling were also found to be reliable allowing coaches and practitioners to quantitatively and reliably prescribe sled loading to maintain a consistent training stimulus across zones of training identified within the load-velocity profile. A large degree of between athlete variability exists in both sled pushing and pulling; a Vdec of 50% resulted in a confidence interval for load ranging 45-85 % and 71-107% body mass respectively. This suggests that sled pushing has a higher degree of variability in the load required to provide a consistent power training stimulus. The load almost doubles between participants who tolerate load the least to those who tolerate load the most in a youth population sled pushing, a finding that was consistent across all training zones across the mean load-velocity profile of the group. Chapter 3 and 4 further reinforced the need for individual load prescription based off Vdec rather than a set % BMs for all individuals.

8.1.3 Aim 3:

Assess the effectiveness of unresisted and resisted sled-push and sled pull training on sprint performance across a range light, moderate and heavy individualised loads.

Key points to consider

- Both sled pushing and pulling were more effective than unresisted sprinting in improving short distance sprint performance, heavier loads in excess of 50% Vdec seem to provide the greater benefits of increasing initial acceleration, force and power.

- There is a clear trend for greater and more consistent improvements in sprinting force, power and performance over short distances when training with heavier sled loads during both sled pushing and pulling.
- Both forms of resisted RST should be categorized as sprint specific horizontal strength training exercises, with sled pulling suggested to be more specific than sled pushing due to the use of the arm drive.
- Changes in sprint split times were reflected in the force-velocity profiles with sled pulling producing greater effect size change in F_0, Vmax and Pmax than sled pushing following the training intervention. Changes in the sprint force-velocity profile are specific to the training stimulus employed, with heavy sled pulling being particularly effective at improving F_0 and acceleration over 5 m.
- Heavy and moderate sled-pull training significantly improved F_0 and Pmax, while unresisted and lighter loads resulted in small improvements in Vmax. Changes in the sprint force-velocity profile are specific to the training stimulus employed, with heavy sled pulling being particularly effective at improving F_0 and acceleration over 5 m.

Aim 3 conclusion

The results of both training studies in Chapters 5 and 6 suggest that post PHV males with limited training exposure to resisted sprinting may reap the greatest gains in short distance sprint performance with much heavier external load. The loads used in both training studies are higher than the loads used in the majority of previous research in adult populations for both resisted sled pushing and pulling. Sled pushing improved short distance sprint performance but with less specific responses to load compared to pulling. Sled pulling appears to be a more specific form of RST and supports the notion of adaptations being specific to the imposed demands, with heavier loads appearing to favour horizontal force production during the early acceleration phase, whereas lighter loads and unresisted sprinting benefit the transition to maximum velocity phase.

8.1.4 Aim 4:

To provide practical programming guidelines on how to integrate resisted sled training into an athletes training.

Key points to consider

- The Vdec method is recommended over a set %BM for prescribing load during RST. However, it does require a load-velocity (LV) profile to be created for each athlete consisting of one unresisted and at least two resisted sprint trials either side of 50% Vdec.
- Heavier loading parameters may be utilized for more mature young athletes (mid/post PHV) with a higher training age due to the natural ability to develop higher relative horizontal forces as maturity and strength increase.
- A cumulative level of baseline traditional strength training may be required before introducing young athletes to RST and progressing from light to heavier loading schemes.
- Marching and running progressions at low to moderate velocities during both forms of RST can also be utilized to emphasize the forward lean, proper postural control and knee drive for pre PHV athletes as sprinting technique should be a focus point due to neural plasticity and a heightened ability to adapt to technique.
- Heavier loading schemes for resisted sled sprinting can be used in earlier preparatory phases to emphasise developing maximum strength capabilities in a horizontal plane of motion.

- During the latter specific phases as competition approaches, faster running speeds at a lesser loading intensity can be used to develop and maintain power and explosive sprinting capabilities.
- Heavier loads (greater % Vdec) pushed and pulled for higher rep rangers at shorter distances (5 and 7.5 m) are used in the general preparation phase in comparison to the specific preparation phase. Training at such heavy loads for short distances is designed to increase the initial and early acceleration phase of the sprint without causing unnecessary fatigue
- Sled pushing may be favoured as a form of very heavy RST to precede sled pulling during the initial general preparation phase of the strength-speed zone of training to increase total body horizontal strength. This is due to sled pushing being viewed as less specific to sprinting in comparison to sled pulling given the use of the arms to move the sled. The power zone of training is recommended within the continuum of decreasing intensity and increasing load to target the late acceleration phase of training. The prior phases of training at a greater intensity (%Vdec) creates a sustainable platform for athletes to progress to enhancing their task specific speed-strength. Research examining sled loading at lighter loads suggests a targeted improvement in the transition to Vmax phase.

Aim 4 Conclusion

Sprint-specific training should be used to develop speed using RST in the form of both sled pushing and pulling. Coaches need to consider the maturity, competency and training age of young athletes to prescribe the most appropriate sprint-specific modalities as part of a holistic training program that includes traditional resistance training, speed, agility, and sport practice. Different zones of training can provide coaches with a targeted approach to improving specific phases within a sprint. During the earlier preparatory phases, acceleration can be targeted through low velocity RST at higher loading intensities. As competition approaches coaches can target late acceleration and transition to Vmax through higher velocity RST at lower loading intensities. Sled pulling is recommended as a more specific form of RST than sled pushing due to the use of the arm drive. Specific areas of sprint mechanics such as forward body lean, postural control and knee drive can be emphasized within different training zones across both pre PHV and post PHV to reinforce good sprint technique.

8.2 Limitations

It is important for the reader to be cognizant of the following limitations when interpreting the results of this thesis.

- The overall cohort of young athletes consisted of post PHV athletes only. All results within this thesis cannot be applied across the spectrum of childhood and adolescence as differences exist between pre, mid and post PHV athletes.
- Sled pushing and pulling load velocity relationships were largely driven by the effects of body mass during RST. Therefore, the assessment of fat-free mass may have better explained the variability between athletes within a group of post-PHV in both sled push and pulling.
- Kinematic data was limited during the acute study testing sessions due to resources and time constraints. Although unresisted force-velocity profiles and resisted load-velocity profiles were recorded, no contact times, flight times or stride length were recorded during resisted sprint trials.
- Load-velocity profiles were created pre-intervention to prescribe load effectively. However, they were not assessed post-intervention to determine how task specific horizontal strength had improved.

- A second post-testing session was not assessed post-intervention in both sled pushing or pulling to the determine the detraining effect. Given this was the first cumulative block of RST the athletes had undertaken, it is important to assess detraining and also a repeated intervention to determine how athletes would respond to a cumulative stimulus they have already experienced.
- Although some references are made comparing the effects of both RST conditions acutely and longitudinally, sled pushing and pulling were not directly compared with the same athletes in this thesis.

8.3 Future Research Directions

Further cross-sectional research examining relationships between measures of strength and fat-free mass with RST load-velocity profiling will help practitioners to better understand the individual factors that determine the ability of young athletes to tolerate load. Furthermore, more detailed research examining the step kinematic and kinetic data is needed at loads within the three loading and training zones identified in this thesis. Longer term interventions across multiple populations, including pre PHV and young female athletes should be undertaken to determine the effects sex and maturation have on adaptation to training. Training interventions periodised between the preparatory and competitive phases and different loading parameters are needed to determine the optimal dose response in RST at different points in an athlete's season. More research is needed to determine if an athletes' baseline force-velocity profile characteristics influence the optimal selection of load for training in both youth and adult populations (i.e. force or velocity dominance).

8.4 Overall Conclusion

This thesis explored the acute and chronic training responses to RST in young athletes. The results of this thesis further reinforce the limitations to prescription of load by a set % BM. Load can be reliably prescribed in both conditions of RST to young athletes using the Vdec approach to provide a consistent training stimulus across athletes. Both sled pushing and pulling are effective sprint specific modes of training to enhance overall sprint performance. Heavier loads appeared to yield the greatest benefit to young athletes in short distance sprint performance, however a targeted approach to sled loading can influence different phases of the sprint.

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Appendix 1. A summary table of acute/cross sectional studies examining resisted sled pulling and pushing.

Authors	Subjects	Resisted Loads	Key Findings	% Change in Sprint Performance
Lockie et al. (2003) (19)	Healthy male field sport athletes (n=23; mean age 23.1yrs)	12.6 & 32.2% BM sled pulls	Heavier load (32.2% BM) resulted in greater disruption of sprint mechanics compared to lighter load (12.6% BM. Statistically significant differences were found between load in velocity, stride length, flight time (2nd step) and contact time.	Velocity *12.6% BM - ↓ 8.7% *'**32.2% BM - ↓ 22.8% Stride length *12.6% BM - ↓ 10% *32.2% BM - ↓ 24 Flight time (1st & 2nd step) 12.6% BM - ↓25% & 20% *'**32.2% BM - ↓ 40% & 50% Contact time (1st & 2nd step) *12.6% BM - ↑ 10% & 10% *'**32.2% BM - ↑ 19% & 22% Hip flexion *12.6% BM - ↑ 9.4% *32.2% BM - ↑ 15.2%
Murray et al. (2005) (29)	Male rugby and soccer players (n=33; mean age 21.1 yr.)	5, 10,15,20,25,30% BM sled pulls	As load increased, sprint time increase. Stride length decreased significantly as did stride frequency but to a lesser extent as load increased. No specific resistance could be recommended.	Stride length *30% BM – ↓18.7% *(p>0.001)
Maulder et al. (2008) (25)	National and regional competitive male track sprinters (n=10;mean age 20 yr.)	10 & 20% BM sled pulls	Neither load had any significant effect on step angular kinematics. 10% BM had no negative effect on sprint start technique or step kinematic variables. 10% BM load may be more beneficial than 20% BM load.	10m sprint time *10% BM - ↑ 8% *20% BM - ↑14% Stride length (3rd & 4th step) 10% BM - ↓ 8% & 9% *20% BM - ↓ 12% & 11% Flight distance (3rd & 4th step)

				10% BM - ↓ 8% & 9% *20% BM - ↓ 12% & 11%
Cronin et al. (2008) (9)	Mixed sport athletes (track sprinters, beach sprinters and rugby union players) (n=20; mean age 19.9)(16 male & 4 female)	15 & 20% BM sled pulls	Stride length and stride frequency both reduced as the sled load increased, but stride length reduced significantly more with a heavier load of 20% BM in comparison to 15% BM.	15m Swing Phase Duration *15% BM = 6.81 *'**20% BM =11.2 Stance phase duration *15% BM =12.8% *'**20% BM =15.2%
Alcaraz et al. (2008) (1)	Competitive sprints and long jump athletes (n=18; mean age 22 yr.) (11 male &7 female)	16% BM sled pull	Significant trunk angle forward lean increase was seen in men and not women. Stride length decreased at 16% BM in both groups. (Max Velocity)	Velocity *Men - ↓ 12% *Women - ↓ 14% Stride length *Men - ↓8% *Women – ↓ 8% Body lean increase (Men) *Tdown – ↑ 31.2% *Tmid – ↑ 31.2% *Toff – ↑ 40%
Alcaraz et al. (2009) (2)	Male competitive track & field athletes(n=26; mean age 20 yr.)	6, 10 & 15% BM sled pulls	Developed a regression equation to optimise sled load in accordance with keeping the athlete max velocity above 90% (Max Velocity).	Velocity *6%BM = ↓7.4% *10% BM = ↓10.5% *15% BM = ↓ 15.4%

Keogh et al. (2010) (16)	Resistance trained males (n=6;mean age 27 yr.)	171.2 KG heavy sled pull (=169% BM of group mean.	Statistically significant joint angle differences occurred between the acceleration phase and max velocity phase during heavy sled pull but step rate and ground contact did not. Step length differed significantly. Athletes may benefit from heavy sled pulls as specific strength and power exercise.	Trunk angle †Max velocity – ↑ 46% Thigh angle †Max velocity – ↑ 28% Knee angle †Max velocity – ↑ 6.4% Step length †Max velocity – ↑ 28.1% †($p<0.01$) between variables (acceleration & max velocity)
Linthorne & Cooper (2013) (17)	Male rugby players (n=6; mean age 20 yr.)	5, 10, 15, 20, 25 and 30%	Dynamic coefficient of friction remained constant with increasing sled load. Substantial differences in the coefficient of friction was found between surfaces. Rate of increase in 30m time with increasing sled weight differed significantly on the hockey surface.	Pairwise comparative test of surfaces †Athletics – Hockey = ES 4.9 †Rugby – Hockey = ES 5.7 †Football – Hockey = ES 3.5 †($p<0.05$) between variables (surfaces listed above)
Andre et al. (2012) (3)	No subjects were used in this study	44.8kg, 90kg and 136.2kg	The methods used to determine both static and dynamic co-efficient of friction were highly reliable.	44.8KG Static – CV = 2.2% Dynamic – CV =1.6% 90KG Static – CV = 3% Dynamic – CV = 3.7%

				136.2 KG Static – CV =2.7% Dynamic – CV = 1.0%
Martinez-Valencia et al (2013) (21)	Male sprinters (n=8; mean age 18.6 yr.)	8, 13 and 18% BM sled pulls	The weight of the sled should be scaled for the athlete's power to weight ratio, rather than for the athlete's bodyweight.	Correlation between lower body power and increase in sprint time with increasing sled weight CMJ height – r=0.73 Peak power in CMJ – r=0.81 Squat jump – r=0.80
Okkonen and Häkkinen (2013) (31)	Male competitive track and field athletes (n=9, mean age =24 yr.)	10 & 20% BM sled pulls	Performance time in the block start (10m) correlated strongly with sled pulling. Sled pull training is recommended to induce positive changes in gluteus maximus activation.	*Sled pulling at both loads had increased levels of EMG activity of GM compared to block start EMG activity compared to block start *10% BM - ↑ VL *20 BM = ↓BF
Rumpf et al. (2014) (35)	Male children (n=35; mean age 13 yr.) (19 Pre PHV & 16 mid/post PHV)	2.5, 5, 7.5 and-10% BM sled pulls	Loads of ≥ 5%BM caused a significant increase in 30m sprint time. Pre-pubertal boys were slowed by 50% more than circa/post –pubertal boys at the same relative load.	30m sprint time 2.5% BM Pre PHV = ↑ 4.7% Mid/post PHV = ↑4.2% 5% BM *Pre PHV = ↑ 7.9% *Mid/post PHV = ↑ 6% 7.5% BM *Pre PHV = ↑ 10.6% *Mid/post PHV = ↑ 7.2% 10% BM *Pre PHV = ↑ 13.6% *Mid/post PHV = ↑ 9%

Martinez-Valencia et al. (2014) (22)	Male competitive sprinters (n=7) and team sport athletes (n=14) (n=21 mean age 18yr)	5, 10, 15, 20, 25, 30% BM sled pulls	SL decreased across all resisted conditions. SF decreased significantly at loads over 15% Bm.	See table 1
Kawamori et al. (2014) (14)	Physically active collegiate team sport males (n=10; mean age 28 yr.)	10 & 30% BM sled pull	10% BM had minimal impact on GRF where as 30% BM resulted in significantly greater values of net horizontal and propulsive impulses.	5m mean sprint velocity *10% BM = ↓ 6.9% *'**30% BM = ↓22.4% Contact time 10% BM = ↑ 2.9% *'**30% BM = ↑ 12.2% Net horizontal impulse 10% BM = ↑ 3.8% *'**30% BM = ↑ 22.6% Propulsive impulse 10% BM = ↑ 2.4% *'**30% BM = ↑ 19.3%
Whelan et al. (2014) (44)	Physically active males (n=12; mean age 22.5 yr.)	Between 25%-30% BM	The results using typical error data did not provide strong evidence of post activation potentiation in 10-m sprint performance after resisted sprinting.	Pre and post test scores Velocity =0% Step rate = 1.4% Contact Time = 2.8%
Maddigan et al. (2014) (20)	Healthy resistance trained men (n=10; mean age = 24.6yr)	Individual 20 step maximum determination test. Group mean = 240.5 ± 31.2 KG	The squat provided higher lower erector spinae activation, whereas the sled push had superior gastrocnemius activation.	61.2% greater gastrocnemius EMG with the sled exercise and 74.5% greater erector spinae EMG activity with the squat.

Cottle et al. (2015) (7)	Collegiate Field and court sport athletes (n=17; mean age = 21 yr.) (10 male, 7 female)	10 & 20% BM sled pulls	20% BM was significantly greater than unresisted in both legs and also significantly greater in the front leg than 10% BM to increase propulsive GRF impulse.	Propulsive GRF impulse Front Leg *10% BM = ↑ 11.1% *'**20 % BM = ↑ 20% Back Leg 10% BM = ↑ 5.2% *20 % BM = ↑14.2% *(p<0.001) from unloaded **(p<0.001) between loads
Martinez-Valencia et al. (2015) (23)	Young experienced competitive sprinters (n=23; mean age 17 years) (17 male & 6 female)	10, 15 & 20% BM sled pulls	RFD peak during the first step with 15 & 20% BM significantly increased when compared to the 10% BM condition.	RFD peak *15% BM = ↑ 26.9% *20% BM = ↑ 41.2%
Winwood et al. (2015) (45)	Male strongman athletes (n=6, mean age 24 yr.)	171.2KG (=151% group mean BM) Heavy squat	Significant kinematic and kinetic differences were found between variables with the sled pull yielding much higher peak and mean anterior forces. Significant differences were also noted in the mean ratio of forces at the start between each variable. The sled pull demonstrated greater horizontal force orientation with the squat demonstrating force in the vertical direction.	Mean vertical force †Squat = ↑48.5% Mean anterior force †Heavy sled = ↑ 92.5% Mean ratio of forces applied onto the ground. †Heavy sled - 39.3% †Squat – 0.2% †(p<0.001) between variables (sled pull & squat)
Waller et al. (2016) (43)	Division II female athletes (n=14, mean age 19.9)	29.5, 39.5, 44.5, 49.5, 64.5, 89.5KG	Acute effects demonstrate that the greater loads during sled pushing increase sprint time emphasizing force production with a decrease in	Peak sprint time (sec) Unresisted = 3.22 ± 0.10 29.5KG = 26%*

			sprinting velocity and representing a shift in a force-velocity curve.	39.5KG = 32%* 44.5KG = 37%* 49.5KG = 40%* 64.5KG = 48%* 89.5KG = 58%*
Winwood et al. (2016) (46)	Resistance trained team sport males (n=22, mean age	75 and 150% BM	75% body mass sled pull can be an effective preload stimulus for improving subsequent sprint performance provided that adequate recovery (8-12 minutes) is allowed.	75% BM ES ES ES Baseline 0-5m 0-10m 0-15m 4min 0.04 0.09 0.09 8min 0.33 0.31 0.24 12min 0.24 0.26 0.22 150% BM ES ES ES Baseline 0-5m 0-10m 0-15m 4min -0.28 - 0.28 - 0.13 8min -0.11 -0.19 -0.01 12min 0.00 -0.22 -0.01
Bentley et al. (2016) (6)	Resistance trained males (n=14, mean age 26.7 yr.)	>10% of max velocity sled pulls	Greater net horizontal mean force, net horizontal impulses, propulsive mean force and propulsive impulses were found between weighted and unweighted. The waist harness led to greater net horizontal impulse when compared to shoulder attachment.	Net horizontal mean force *Shoulder = 8.4% *Waist = 15.2% Net horizontal impulse *Shoulder = 17.9% *†Waist = 22.5% Propulsive mean force Shoulder = ↑ 4.75% *Waist =↑10.5% Propulsive impulse *Shoulder = ↑17.1% *Waist = ↑20.5%

				†= p< 0.05 between variables (waist and shoulder)
Cross et al. (2017) (11)	Recreational mixed sport athletes (n=12;mean age 27 yr.) and competitive sprinters (n=15;mean age 24 yr.)	20-120% BM sled pulls	Sprinters generated greater statistically significant Pmax than recreational athletes but did not for Fopt or Lopt. Optimal loading was found to be between 69-96% BM, much greater than previous research guidelines.	Pmax relative to BM †Sprinters generated 26.4% more than recreational athletes Fopt Sprinters =82% BM Recreational =78% BM Lopt Sprinters = 70 – 96% BM Recreational = 69 – 91% BM †(p<0.05) between variables (sprinters v recreational)
Cross et al. (2017) (10)	No subjects were used in this study	33.1kg, 55.6kg, 77.8kg and 99.6kg mechanical sled pulls	Friction coefficient does not change with sled mass, but is instead dependent on towing velocity. All variables were determined as reliable.	ICC>0.99 CV<4.3%
Martinez-Valencia et al. (2017) (24)	Volunteer male athletes (n=22; mean age 22.6 yr.)	5, 10,15,20,25,30% BM sled pulls Half squat	No clear correlation between the rate of increase in sled-towing time with increasing sled weight and normalized 1RM half-squat performance	10 m time & 1RM half squat r=-0.11; 90% CI -0.45 to 0.26 20 m time & 1RM half squat r = –0.02; CI –0.38 to 0.34
Wong et al. (2017) (47)	Recreationally trained field sport men (n=20, mean age 22yr)	30 % BM	A decrease in sprint time occurred over the first 5m which may be a result of PAP. Coaches should test athletes individually to determine the	0-5m Baseline - 1.13 ± 0.08 seconds 0-5m PAP = 1.08 ± 0.08 seconds Rest Intervals 2-12 minutes

			optimal rest interval after a 30-m 30% BM sled tow to enhance acute sprint speed.	
Petrakos et al., (2017) (33)	Female field sport athlete (n=21; 20.8 yr.)	15% BM	MRSL is a reliable measure for determining the RSS load at which an individual can no longer accelerate during a single RSS effort over 0-20 m	MRSL = 20.7 – 58.9% BM
Seitz et al. (2017) (39)	Male rugby players (n=20; mean age 18.4yr)	75 and 125% BM	20m sprint performance is potentiated 4-12 minutes following a sled push of 75%BM but found it impaired at 125%BM.	75% BM Baseline – 3.28 ± 0.14 ES 15s – 0.07 4min – -0.22 8min – -0.42* 12 min – -0.36* 125% BM Baseline – 3.30 ± 0.20 15s – 0.64* 4min – 0.53* 8min – 0.41* 12 min – 0.34
*p<0.05 from unloaded conditions, **p<0.05 between loaded conditions, † between variables listed BM= body mass, Tdown = instant of touchdown. Tmid = instant of midstance, Toff = instant of take-off, ES = Effect size, CV=coefficient of variation, PHV = peak height velocity, GRF = ground reaction force, RFD = rate of force development, EMG = electromyogram, Pmax = maximal Power, Fopt = optimal force, Lopt = optimal load, ICC=interclass correlation coefficient, r= correlation coefficient, CI = confidence interval, PAP = Post activation potentiation, MRSL = Maximum resisted sled load, RSS = Resisted sled sprint.				

Appendix 2. Ethics Approval Form

WCU
WEST CHESTER UNIVERSITY

Office of Research and Sponsored Programs | West Chester University | Filano Hall
West Chester, PA 19383 | 610-436-3557 | www.wcupa.edu

Protocol ID # 20160628
This Protocol ID number must be used in all communications about this project with the IRB.

TO: Kenneth Clark and Michael Cahill

FROM: Melissa A. Reed, Ph.D.
Co-Chair, WCU Institutional Review Board (IRB)

DATE: 6/28/2016

Project Title: The effectiveness of resisted sprinting to improve acceleration in adolescent athletes
Date of Approval: 6/28/2016

☒**Expedited Approval**

This protocol has been approved for a period of one year. Approximately two months prior to the approval end date, you will receive a Continuing Review of Research form. Per Federal regulations, this form must then be completed as soon as possible and returned to the IRB at irb@wcupa.edu , even if the project has been completed or discontinued. Any revisions to this protocol that are needed before that time will require approval by the WCU IRB. Please see www.wcupa.edu/research/irb.aspx for more information.

Any adverse reaction by a research subject is to be reported immediately through the Office of Research and Sponsored Programs via email at irb@wcupa.edu.

Signature:

Melissa A. Reed

Co-Chair of WCU IRB

West Chester University is a member of the State System of Higher Education

Appendix 3. Parental Informed Consent, Student Assent and Medical Questionnaire Forms for Chapters 3 – 6.

West Chester University Institutional Review Board

Parental Informed Consent Form

Please read the following before you agree to your child's participation.

Investigator's: Ken Clark (610-436-2109) & Micheál Cahill (214-984-6776)

Nature and Purpose of the Study:

The reason for this research is to see how young athletes respond to pulling and pushing loads. The benefits of this training for your son may include improved sprinting and jumping performance. The results of the study will help him understand his fitness levels.

Explanation of Procedures

Before any testing, your son will be made aware of what to expect during the exercise session.

The session begins with a 15-minute warm-up which includes sprints. This is followed by tests in height, weight, jumps, sprints and deadlift. Height will be measured using a tape measure and weight measured on a standard bathroom scale. For the jump test, your son will have three tries for horizontal jump and three tries for vertical jump. Your son will have one-minute rest between jumps.

For the sprint testing, your son will perform two 30-yard sprints. Your son will have four minutes between sprints to allow him to recover. Following these pre-tests your son will be assigned to one of four resisted sprint training groups.

Your son will train twice a week for 8 weeks. Each training session will last 90 minutes. Following this 8-week period, your son will be tested again. Participation will not require any extra time outside of the normal school conditioning program. All testing and training sessions will be completed at the athletic facilities in Jesuit College Preparatory School of Dallas.

Experimental Medical Treatments or Procedures: None

Foreseeable Risks: There are no added risks other than those already exist for taking part in the off-season conditioning program.

Benefits: Your son may find the information collected useful in understanding how he performs and help him plan future fitness goals.

Confidentiality: Confidentiality will be maintained. Only the investigators will have access to the identity of participants.

Compensation for Participants: None

Contact Person (s) Dr. Ken Clark at kclark@wcupa.edu. Micheál Cahill at mcahill@jesuitcp.org. The West Chester University office of Research and Sponsored Programs at 610-436-3557.

Withdrawal Notice: Your son has the right to stop participating at any time.

____

Printed Name of Parent or Guardian

__________________________________ _____________

Signature of Parent or Guardian Date

____ ________

Signature of Investigator or Designee Date

Student Assent Form

West Chester University Institutional Review Board

Student Informed Consent Form

Please read the following before you agree to participate.

Investigator's: Ken Clark (610-436-2109) & Micheál Cahill (214-984-6776)

Nature and Purpose of the Study:

The reason for this research is to see how young athletes respond to pulling and pushing loads. The benefits of this training for you may include improved sprinting and jumping performance. The results of the study will help you understand your fitness levels.

Explanation of Procedures

Before any testing, you will be made aware of what to expect during the exercise session.

The session begins with a 15-minute warm-up which includes sprints. This is followed by tests in height, weight, jumps, sprints and deadlift. Height will be measured using a tape measure and weight measured on a standard bathroom scale. For the jump test, you will have three tries for horizontal jump and three tries for vertical jump. You will have one-minute rest between jumps.

For the sprint testing, you will perform two 30-yard sprints. You will have four minutes between sprints to allow you to recover. Following these pre-tests, you will be assigned to one of four resisted sprint training groups.

You will train twice a week for 8 weeks. Each training session will last 90 minutes. Following this 8-week period, you will be tested again. Participation will not require any extra time outside of the normal school conditioning program. All testing and training sessions will be completed at the athletic facilities in Jesuit College Preparatory School of Dallas.

Experimental Medical Treatments or Procedures: None

Foreseeable Risks: There are no added risks other than those already exist for taking part in the off-season conditioning program.

Benefits: You may find the information collected useful in understanding how he performs and help plan future fitness goals.

Confidentiality: Confidentiality will be maintained. Only the investigators will have access to the identity of participants.

Compensation for Participants: None

Contact Person (s) Dr. Ken Clark at kclark@wcupa.edu. Micheál Cahill at mcahill@jesuitcp.org. The West Chester University office of Research and Sponsored Programs at 610-436-3557.

Withdrawal Notice: You has the right to stop participating at any time.

____

Printed Name of Participant

_________________________________ ____________

Signature of Participant Date

_______________________________________ _______

Signature of Investigator or Designee Date

West Chester University

****PHYSICAL HEALTH AND MEDICAL HISTORY QUESTIONNAIRE****

Project Title: What are the acute and chronic responses to sled pulling and pushing in adolescent athletes?

Principal Investigator, address, phone:

Dr. Kenneth Clark	Micheál Cahill
Principal Investigator	Co-Principal Investigator
Department of Kinesiology	Jesuit Athletic Performance
West Chester University	Jesuit College Preparatory School of Dallas
610-436-2109	214-984-6776

Subject ID #:
Sex:
Age:
Occupation:

1. Do you, or have you, ever had? (check if yes)

_________ Pain in your heart or chest
_________ Heart attack
_________ Rheumatic fever
_________ Disease of the arteries
_________ Varicose veins
_________ Heart murmur
_________ Any heart problem
_________ Abnormal EKG
_________ Extra or skipped heart beats
_________ Phlebitis
_________ Dizziness or fainting spells
_________ Stroke
_________ High blood pressure
_________ Badly swollen ankles
_________ Cough on exertion
_________ Marfan's Syndrome
_________ Coughing of blood
_________ Anaemia
_________ Diabetes
_________ Epilepsy
_________ Bronchitis
_________ Asthma
_________ Pneumonia
_________ Abnormal chest X-ray
_________ Other lung diseases
_________ Nervous/emotional problems
_________ Back, arm, legs or joint injuries
_________ Back pain
_________ Swollen, stiff or painful joints
_________ Arthritis of arms or legs
_________ Scarlet fever

Explanation or comments:

2. List any medication or drugs you are now taking:

3. What was the date of your last medical exam: ___________ Were the results normal? __________

If no, explain:

4. Do you know of any medical problem that might make it dangerous or unwise for you to participate in vigorous exercise?

Yes ________ No _________

If yes, explain:

5. Have you had any head, chest or limb fractures or sprains that occurred within the last year?

Yes ________ No _________

If yes, explain:

6. Have you had a concussion within the last year or more than two concussions in your lifetime?

Yes ________ No _________

If yes, explain:

7. Are you taking any dietary or over the counter supplements?
Yes _______ No ________

8. If you are taking any dietary or over the counter supplements, please specifically identify whether you are taking the following:

________ Diuretics
________ Weight loss pills
________ Ephedra
________ Bitter Orange (*Citrus aurantium*)
________ Lobelia (*Lobelia inflate* or Indian tobacco)
________ Yohimbe (*Pausinystalia yohimbe* or Tree Bark)

Please identify any other supplements you are taking:

9. Have you or any of your male first degree blood relatives (i.e. father, brother, son) had any of the following before the age of 55?

________ Heart attack
________ Sudden death
________ Coronary revascularization

10. Have you or any of your female first degree blood relatives (i.e. mother, sister, daughter) had any of the following before the age of 65?

________ Heart attack
________ Sudden death
________ Coronary revascularization

11. Have you or any of your blood relatives had any of the following:

________ Stroke
________ High blood pressure
________ Elevated cholesterol
________ Obesity
________ Congenital heart disease
________ Heart operations
________ Diabetes

12. Have you ever smoked:

cigarettes ________ Age Started _____ Age quit _____ No. per day _______

cigars ________ Age Started _____ Age quit _____ No. per day _______

pipe ________ Age Started _____ Age quit _____ No. per day _______

13. What is your approximate weight now? __________

14. Are you currently involved in a regular exercise program? If yes, indicate the type and amount of exercise:

15. Do you regularly walk or run one or more miles continuously? _______Do you frequently participate in sports? _______

If yes, which ones? ______________________What is the average number of times per month? ________

Did you participate in high school or college varsity sports? _______ If yes, which ones? ____

16. Do you experience discomfort, shortness of breath or pain with moderate exercise? __________________________

17. Explain any other significant medical problems or conditions you have:

__________________________ Signature of investigator

__________________________ Signature of participant

Date: __________________

Date: __________________

Appendix 4 Approval letters and recruitment scripts

JESUIT
COLLEGE PREPARATORY
SCHOOL OF DALLAS

JESUIT
COLLEGE PREPARATORY
SCHOOL OF DALLAS

April 26th, 2016

To Whom It May Concern,

I am giving permission for the student athletes at Jesuit College Preparatory School to participate in a research study within the context of their normal off-season conditioning program. The Jesuit Athletic Performance Coaching staff, along with scientific collaborators from West Chester University, will be conducting the research study. I understand that the purpose of the research study is to determine the acute and chronic responses to resisted sprint training in adolescent athletes.

Parental informed consent and child assent will be obtained from both the subjects and their parents/guardians. The coaches and/or research investigators will review the informed consent and child assent documents with the subjects and their parents to ensure that all content is fully understood. All consent forms will be collected at the school prior to data collection. Participation is strictly voluntary and it will be clearly stated that there are no negative repercussions for choosing not to participate in the research study. The confidentiality of each student's individual information will be maintained in any publications or presentations regarding this study.

The resistance training and testing activities are part of the normal off-season conditioning activities, and therefore the foreseeable risks and potential for injury are no greater than the minimal risk the students are exposed to from training on a daily basis. The benefits to the individual students and to the Jesuit athletic department as a whole are several-fold. On an individual basis, the students can use the information to understand the basis of performance, their individual fitness levels, and devise training goals and strategies. More broadly, the research has implications for understanding the efficacy of different types of resistance training programs in developmental athletes, and this research may advance the scientific understanding of the factors that determine exercise performance.

Once again, I am giving full permission for the student athletes at Jesuit College Preparatory School to participate in a research study conducted by the Jesuit Athletic Performance Staff and collaborators from West Chester University

Please contact me with any questions or for further information.

Sincerely,

Steve Koch
Athletic Director

Jeremy Weeks
Director of Athletic Performance

Jesuit College Preparatory School of Dallas

Office of the Principal

April 26, 2016

To Whom It May Concern,

I am giving permission for the students at Jesuit College Preparatory School to participate in a research study within the context of their normal off-season conditioning program. The Jesuit Athletic Performance Coaching staff, along with scientific collaborators from West Chester University, will be conducting the research study. I understand that the purpose of the research study is to determine the acute and chronic responses to resisted sprint training in adolescent athletes.

Parental informed consent and child assent will be obtained from both the subjects and their parents/guardians. The coaches and/or research investigators will review the informed consent and child assent documents with the subjects and their parents to ensure that all content is fully understood. All consent forms will be collected at the school prior to data collection. Participation is strictly voluntary and it will be clearly stated that there are no negative repercussions for choosing not to participate in the research study. The confidentiality of each student's individual information will be maintained in any publications or presentations regarding this study.

The resistance training and testing activities are part of the normal off-season conditioning activities, and therefore the foreseeable risks and potential for injury are no greater than the minimal risk the students are exposed to from training on a daily basis. The benefits to the individual students and to the Jesuit athletic department as a whole are several-fold. On an individual basis, the students can use the information to understand the basis of performance, their individual fitness levels, and devise training goals and strategies. More broadly, the research has implications for understanding the efficacy of different types of resistance training programs in developmental athletes, and this research may advance the scientific understanding of the factors that determine exercise performance.

Once again, I am giving full permission for the students at Jesuit College Preparatory School to participate in a research study conducted by the Jesuit Athletic Performance Staff and collaborators from West Chester University.

Please contact me with any questions or for additional information.

Sincerely,

T. Garrison

Thomas E. Garrison
Principal
Jesuit College Preparatory School

12345 Inwood Road • Dallas, Texas 75244 • 972-387-8700 • www.jesuitcp.org

E-mail Recruitment Script - Parents

Dear ______________,

My name is __________and I am a member of the Athletic Performance Staff at Jesuit College Preparatory School. We are about to begin a research with West Chester University (PA). We thought that you and your son may be interested in the study.

The purpose of the study is to look at the effect of resisted sprinting on youth athletes. Your son may benefit in speed, jumping and strength. Participation will not require any extra time outside of the normal school conditioning program. Participation is completely voluntary, and there will be no penalties from the team or the school if your son decides not to participate.

Further information will be given to your child at school. If he is interested, a Consent Form will be given for you to review. After you review the form, please contact me with any questions. If you have no questions, you can sign and return the form to me at Jesuit College Prep. We can then proceed to have your son sign a Student Assent Form prior to the beginning of the research data collection.

Thank you in advance for your considerations and please contact me with any questions.

Sincerely,

____

E-mail Recruitment Script - Student

Dear ______________,

My name is __________and I am a member of the Athletic Performance Staff at Jesuit College Preparatory School. We are about to begin a research with West Chester University (PA). We thought that you may be interested in the study.

The purpose of the study is to look at the effect of resisted sprinting on youth athletes. You may benefit in speed, jumping and strength. Participation will not require any extra time outside of the normal school conditioning program. Participation is completely voluntary, and there will be no penalties from the team or the school if you decide not to participate.

Further information will be given to you at school. If interested, a Consent Form will be given for your parent or guardian to review. Once your parent/guardian signs and returns the form, we can then proceed to have you sign a Student Assent Form prior to the beginning of the research data collection.

Thank you in advance for your considerations and please contact me with any questions.

Sincerely,

____

Appendix 5 Chapter 2 Abstract

Resisted sprinting in the form of both sled pushing and pulling is a popular training method to improve speed capability, although research has been biased towards investigating the effects of sled pulling. Practitioners need to understand whether the sled push and pull offer differential training effects, and hence their utility in influencing sprint kinematics and kinetics for targeted adaptation. Furthermore, there are a number of recent developments in loading and assessment that warrant discussion, given the impact of these techniques on understanding the load-velocity relationship and optimizing horizontal power output. Finally, some thoughts regarding load prescription are shared with the reader.

Key Words

Resisted sled sprinting, sled pushing, sled pulling, acceleration, horizontal force, horizontal strength training.

Appendix 6. Chapter 3 Abstract

The purpose of this study was to examine the usefulness of individual load–velocity profiles and the between-athlete variation using the decrement in maximal velocity (Vdec) approach to prescribe training loads in resisted sled pulling in young athletes. Seventy high school, team sport, male athletes (age 16.7 ± 0.8 years) were recruited for the study. All participants performed one unresisted and four resisted sled-pull sprints with incremental resistance of 20% BM. Maximal velocity was measured with a radar gun during each sprint and the load–velocity relationship established for each participant. A subset of 15 participants was used to examine the reliability of sled pulling on three separate occasions. For all individual participants, the load–velocity relationship was highly linear ($r > 0.95$). The slope of the load–velocity relationship was found to be reliable (coefficient of variation (CV) = 3.1%), with the loads that caused a decrement in velocity of 10, 25, 50, and 75% also found to be reliable (CVs = <5%). However, there was a large between-participant variation (95% confidence intervals (CIs)) in the load that caused a given Vdec, with loads of 14–21% body mass (% BM) causing a Vdec of 10%, 36–53% BM causing a Vdec of 25%, 71–107% BM causing a Vdec of 50%, and 107–160% BM causing a Vdec of 75%. The Vdec method can be reliably used to prescribe sled-pulling loads in young athletes, but practitioners should be aware that the load required to cause a given Vdec is highly individualized.

Keywords: resisted sled sprinting; acceleration; horizontal strength training; reliability.

Appendix 7. Chapter 4 Abstract

Resisted sled pushing is a popular method of sprint-specific training; however, little evidence exists to support the prescription of resistive loads in young athletes. The purpose of this study was to determine the reliability and linearity of the force-velocity relationship during sled pushing, as well as the amount of between-athlete variation in the load required to cause a decrement in maximal velocity (Vdec) of 25, 50 and 75%. Ninety (n=90) high school, male athletes (age 16.9 ± 0.9 years) were recruited for the study. All participants performed one unresisted and three sled-push sprints with increasing resistance. Maximal velocity was measured with a radar gun during each sprint and the load-velocity relationship established for each participant. A subset of 16 participants examined the reliability of sled pushing on three separate occasions. For all individual participants, the load-velocity relationship was highly linear ($r > 0.96$). The slope of the load-velocity relationship was found to be reliable (CV = 3.1%), with the loads that cause a decrement in velocity of 25, 50 and 75% also found to be reliable (CVs = <5%). However, there was large between-participant variation (95%CI) in the load that caused a given Vdec, with loads of 23-42% body mass (%BM) causing a Vdec of 25%, 45-85%BM causing a Vdec of 50% and 69-131%BM causing a Vdec of 75%. The Vdec method can be reliably used to prescribe sled-push loads in young athletes, but practitioners should be aware that the load required to cause a given Vdec is highly individualized.

Key Words

Resisted sprinting, acceleration, horizontal strength training.

Appendix 8. Chapter 5 Abstract

Sled pushing is a commonly used form of resisted sprint training, however little empirical evidence exists, especially in youth populations. The aim of this study was to assess the effectiveness of unresisted and resisted sled pushing across multiple loads. Fifty high school athletes were assigned to an unresisted (n=12), or 3 resisted groups; light (n=14), moderate (n=13) and heavy (n=11) resistance that caused a 25, 50 and 75% velocity decrement in maximum sprint speed, respectively. All participants performed two sled push training sessions twice weekly for 8 weeks. Before and after the training intervention, the participants performed a series of jump, strength and sprint testing to assess athletic performance. Split times between 5 – 20 m improved significantly across all resisted groups (all $p<0.05$, $d = 0.34 – 1.16$) but did not improve significantly with unresisted sprinting. For all resisted groups gains were greatest over the first 5 m ($d = 0.67$-0.84) and then diminished over each subsequent 5 m split ($d = 0.08$-0.57). The magnitude of gains in split times was greatest within the heavy group. Small but non-significant within group effects were found in pre to post force-velocity profiles. There was a main effect of time but no interaction effects as all groups increased force and power, although the greatest increases were observed with the heavy load ($d = 0.50$-0.51). The results of this study suggest that resisted sled pushing with any load was superior to unresisted sprint training, and that heavy loads may elicit the greatest gains in sprint performance over short distances.

Keywords: Horizontal resistance training; resisted sprinting; acceleration

Appendix 9. Chapter 6 Abstract

Although resisted sled towing is a commonly used method of sprint specific training, little uniformity exists around training guidelines for practitioners. The aim of this study was to assess the effectiveness of unresisted and resisted sled-pull training across multiple loads. Fifty-three male high school athletes were assigned to an unresisted (n=12), or one of 3 resisted groups; light (n=15), moderate (n=14) and heavy (n=12) corresponding to loads of 44 ± 4 %BM, 89 ± 8 %BM and 133 ± 12 %BM that caused a 25, 50 and 75% velocity decrement in maximum sprint speed, respectively. All participants performed two sled-pull training sessions twice weekly for eight weeks. Split times of 5, 10 and 20 m improved across all resisted groups (d = 0.40 – 1.04, $p<0.01$) but did not improve with unresisted sprinting. However, the magnitude of the gains increased most within the heavy group, with the greatest improvement observed over the first 10 m *(d* ≥ 1.04). Changes in pre to post intervention force-velocity profiles were specific to the loading prescribed during training. Specifically, F_0 increased most in moderate to heavy groups *(d* = 1.08 – 1.19); Vmax significantly decreased in the heavy group but increased in the unresisted group (d = 012. – 0.44); whereas, Pmax increased across all resisted groups (d = 0.39 – 1.03). The results of this study suggest that the greatest gains in short distance sprint performance, especially initial acceleration, are achieved using much heavier sled loads than previously studied in young athletes.

Keywords: Horizontal strength training; resisted sprinting; acceleration; youth

Appendix 10. Chapter 7 Abstract

There is a renewed interest is resisted sled training, however little uniformity exists regarding the integration of best practices in resisted sled training for young athletes. This article reviews the prescription of load, methods of resisted sled training and the integration of sprint specific periodized training blocks during the preparatory phase to elicit the greatest gains within different phases of sprint performance such as early, late acceleration and the transition to maximum velocity. A targeted, long-term approach to resisted sled training may enable more effective development of speed in young athletes.

Appendix 11 Speed Development in Young Athlete (Book Chapter)

Appendix 11 comprises of the following published book chapter:

Oliver JL, Cahill M, Uthoff A. (2019) "Speed Training for Young Athletes" Lloyd, R. S. (Ed.), Oliver, J. L. (Ed.). Strength and Conditioning for Young Athletes. London: Routledge, https://doi.org/10.4324/9781351115346

ABSTRACT

The ability to sprint is a fundamental motor skill and speed is a distinguishing characteristic of successful performance in many sports. Despite the importance of speed to long-term athletic development there are a lack of evidence-based training guidelines to improve the sprint performance of young athletes. This chapter will describe how speed naturally develops throughout childhood and adolescence, pointing to the importance of increasing stride length, propulsive and vertical force and stiffness. The chapter will also demonstrate that non-specific forms of training, including plyometric, resistance and combined training, can transfer benefits to sprint speed in young athletes. However, it is sprint-specific training that may offer the greatest potential to increase speed and this chapter will review evidence and provide guidelines for the use of sprint-specific training in young athletes. This includes the use of unresisted forward and backward sprinting as well as resisted sprinting that consider the individual ability of each athlete to work against external load.

INTRODUCTION

Speed is a desirable characteristic that has been associated with successful sports performance in young athletes (46). A failure to fully develop sprint speed during childhood may also restrict opportunities as an adult, as speed is often reported to distinguish between adults of differing competitive standards (44). The ability to accelerate and to attain maximal velocity are both components of speed and should be considered in the development of speed during childhood. For the purpose of this chapter, speed will be considered with regards to overground running as this is the most common application of speed in competition and training. The term ‘speed’ will be used as a generic term that ignores the phase of sprinting.

It is clear that all aspects of speed develop through childhood and, as with other components of fitness, improvements have been reported to follow a non-linear process (39, 40, 63). The development of speed throughout childhood will be influenced by increases in muscle cross sectional area and limb length, biological and metabolic changes, morphological alterations to the muscle and tendon, neural motor development as well as biomechanical and co-ordination factors (19). Given the interaction of so many variables, identifying a single primary mechanism responsible for improvements in speed at different stages of growth and maturation is difficult. However, biomechanical analyses can provide useful information regarding the development of speed, which in its simplest form is a function of stride frequency and stride length. Stride frequency decreases slightly during late childhood due to small increases in ground contact time, but this is more than compensated for by larger increases in stride length throughout childhood and adolescence (35, 40).

The developmental changes that underpin natural gains in speed may help to identify the types of training regimes that can be most successful at different stages of growth and development (37, 38, 49). Training can also be considered in terms of both non-sprint specific (e.g. resistance and plyometric training) and sprint-specific training. A large volume of evidence shows that both specific and non-specific sprint training methods can be effective in youth across different levels of maturity (1, 29, 38, 49), although the concept of training specificity would suggest sprint-specific training methods are likely to provide greater benefits (50). This chapter will consider the natural development of speed and how growth and maturity interact with specific and non-specific forms of sprint training.

NATURAL DEVELOPMENT OF SPEED DURING CHILDHOOD AND ADOLESCENCE

Improvements in speed during childhood follow a non-linear process. Twenty years ago, Viru et al. (63) suggested the existence of a preadolescent spurt in speed between the ages of 5-9 years old followed by a second adolescent spurt around the onset of sexual maturation. This developmental trend has recently been confirmed in a large sample of Japanese boys sprinting over a 50 m force plate (40), with an adolescent spurt in speed for boys also confirmed by others (35, 43, 67). However, whether girls experience any adolescent spurt is unclear with conflicting results reported in the literature (39, 41, 55). The pre-pubertal spurt has been attributed to rapid central nervous system development during the first decade of life, with the adolescent spurt primarily attributed to a rise in hormone levels with maturity (19, 63). This means sprint ability is similar in immature boys and girls but developmental rates diverge with the onset of sexual maturation; with boys increasing speed more rapidly as a result of increased testosterone levels and greater lean muscle mass gains, while girls become somewhat disadvantaged by the accumulation of more fat mass (32, 41). It has been suggested that speed development will typically cease during mid-late adolescence for girls who are not involved in sport (55).

Biomechanical factors in the development of acceleration and maximal velocity sprinting

Developmental trends of speed are predominantly based on sprint performances of distances between 25-50 m (63), which will combine elements of both acceleration and maximal speed. Acceleration is associated with longer periods of ground contact, providing the opportunity to generate a large net impulse (51), while maximal velocity sprinting is associated with shorter periods of ground contact and a rapid rate of force development (64). Supporting the specificity of acceleration and maximal speed, Chelly and Denis (10) reported a common variance of only 21% between these two variables in 16 year old children. The authors reported that acceleration was dependent on relative power, whereas a greater absolute power and increased leg stiffness were required for maximal speed. Nevertheless, both acceleration and maximal speed follow the same development trend from a spatiotemporal perspective; with stride length continuously increasing with age while step frequency decreases slightly in late childhood before stabilising in adolescence (40).

More recently, cross-sectional and longitudinal research has also confirmed the importance of leg stiffness, relative vertical stiffness and relative maximal vertical force production on the development of maximal sprint speed in boys (34, 36). Changes in horizontal leg stiffness support a role of growth and increasing leg length and contact length during sprinting, which is the distance covered while in contact with the ground. While absolute force production increases with maturation, it is relative force production that is important for sprint performance. Vertical relative force production during sprinting seems to be an innate quality remaining unchanged with advancing age and maturation (34, 36, 39, 40). Conversely, relative horizontal propulsive forces have been shown to increase with age in boys and girls, particularly during the acceleration phase, thus mirroring the developmental trend for improvements in stride length and speed (39, 40). Collectively, findings from research suggest that as youth mature they spend slightly longer time on the ground, but growth-related changes enable them to cover more distance during the ground contact period, while high levels of stiffness and relative vertical force coupled to maturity-related increases in relative propulsive force allow more mature youth to propel themselves further during the flight phase. From a mechanistic perspective, maturity induced gains in speed may be driven by alterations to intrinsic muscle-tendon characteristics and a shift from more inhibitory to more excitatory neural regulation.

TRAINABILITY OF SPEED DURING CHILDHOOD

Practitioners should consider how different modes of training can influence speed development, as well as how maturation and training age can affect the training response. Sprint-specific training refers to training that involves either free sprinting or adapted forms of sprinting such as, the different forms of resisted sprinting (e.g. sled pushing, sled pulling, parachute, uphill), assisted sprinting (e.g. downhill, towed), backward running and sprinting, and technical sprint training (e.g. sprint mechanics). Non-specific training includes modes of training that do not include sprinting and instead typically involve different forms of resistance training, plyometric training and combined training methods. Non-specific training methods predominantly include movements in a vertical plane (e.g. squatting), but with scope to include horizontal movements. Practitioners should consider the potential benefits of both forms of training, how they may target the determinants of sprint performance (e.g. stiffness, relative propulsive force), and any interactions with maturation and training history.

Non-Sprint Specific Training

Non-specific sprint training typically includes different forms of resistance, plyometric and combined training that predominantly focus on movements in the vertical plane. The ability of these non-specific training methods to transfer to speed gains is supported by the observation that relative vertical force and stiffness are important determinants of speed. In a meta-analysis, Behringer et al. (2) confirmed that resistance training transferred to gains in sprinting in youth, with greater gains at a younger age, in untrained young athletes, and with a greater intensity of training. In a systematic review, Rumpf et al. (49) demonstrated that children who were pre-PHV increased speed most with plyometric training, while children who were post-PHV gained most from combined training. Later review work by Lesinki et al. (29) confirmed combined training as providing the greatest gains in sprint speed for youth. Experimental research has since supported these notions, showing that plyometric training was more beneficial for boys pre-PHV in increasing acceleration compared to strength training being most beneficial for boys post-PHV, although combined training was equally effective across both maturity groups (45). More recently, a meta-analysis from Behm et al. (1) demonstrated that plyometric training was more advantageous at improving speed in youth, and that gains were greater in children versus adolescents and in untrained versus trained youth populations. Table 10.1 provides a selection of studies that have all examined the ability of non-specific training programmes to increase the speed of young athletes (6-9, 11, 15, 18, 23, 26-28, 31, 56, 62, 66).

[INSERT TABLE 10.1 HERE]

The studies shown in Table 10.1 demonstrate that a range of short-term, non-specific training interventions can be effective at improving speed in youth of varied age and maturation, although with more inconsistent results in the most mature athletes. The gains are often above that would be expected from natural development alone in young athletes, with Williams et al. (65) reporting speed improvements at a rate of ~3% per year in 11-16 y old male football players. This would equate to natural gains of about 0.8-1.5% over the 8-16 weeks training periods in the studies included in Table 10.1, with natural gains expected to be lower in those aged 16 and above.

In practice the strength and conditioning coach should consider a longer-term approach that includes and periodises the various forms of non-specific training to promote continued gains in speed and other athletic qualities. Where strength training has been continued for 2 years in young football players this has not only led to considerable improvements in strength compared to controls, but also transferred to small continued gains in sprint speed (25, 52). Training intensity is an important consideration of any training programme. When investigating the effects of resistance training intensity on speed development in young athletes, Lesinki et al. (29) reported the highest training intensity of 80-89 %1RM to be most effective. This may reflect the importance of relative vertical force in speed development in youth (34, 36) and the need for high training intensities to stimulate an improvement of this quality. Practitioners should look to provide sufficient training intensity in non-sprint specific training, with the caveat being that athletes must maintain technical competency under loading.

Sprint-Specific Training

Following the principle of specificity, specific-sprint training aims to promote neurological and musculoskeletal adaptations which are velocity and task dependent (16). Sprint-specific training is commonly understood as performing linear unresisted, resisted, or assisted sprinting interspersed with periods of passive recovery (49). Table 10.2 provides a selection of studies that have examined the effectiveness of specific sprint training programmes to increase sprinting ability in youth at different stages of maturity (3, 4, 20, 26, 33, 42, 47, 53, 54, 57, 60, 62).

[INSERT TABLE 10.2 HERE]

The studies shown in Table 10.2 demonstrate that 6 to 12 weeks of sprint-specific training can be beneficial for increasing straight-line acceleration and maximal velocity sprinting in youth of varied maturation. Given the complex nature of sprinting, unresisted training may refine technique and help promote more effective running patterns (30), while resisted sprinting likely facilitates horizontal force production capabilities (14, 24). Interestingly, the greatest improvements in acceleration performance have been reported following novel sprint training methods, such as backward running see (see Table 10.2) (60). Backward running specifically targets concentric strength (59), a performance characteristic which underpins accelerated sprinting over short distances (22). In currently unpublished work, the authors of this chapter have found both sled pulling and sled pushing with heavy resistive loads to be most effective at improving the acceleration of adolescent athletes. It is important that practitioners familiarise young athletes with any novel training method first, in order to reduce risk of injury and optimise effectiveness.

Notably from Table 10.2 there is no research into the effects of assisted sprint training in youth. This may be due to the fact that it is more difficult to provide assistance than resistance, and it can be difficult to quantify the level of assistance provided. Clark et al. (12) found that when providing motorized pulling assistance to 16-24 y old athletes sprinting on the track, maximal speed increased by nearly 10%. This was due to increased contact length (3.7%), flight length (13.1%) and flight time (3.4%), while ground contact time was reduced (5.2%). The observed changes reflect a requirement to apply vertical forces to the ground at a faster rate and this could provide a beneficial stimulus if repeated consistently during training; albeit, research is needed to confirm this (12). Personal communication with the authors also revealed that younger sprinters found it difficult to maintain form during assisted sprinting and were not subsequently included in the study. It may be that young athletes need a perquisite level of strength or sprint training history before being able to tolerate assisted sprints.

PRACTICAL APPLICATIONS

Earlier chapters of this text provide guidelines for non-sprint specific training, including strength and power training (Chapter 7), weightlifting (Chapter 8) and plyometric training (Chapter 9). Subsequently, this chapter will provide practical applications pertaining to the use of sprint-specific training.

Sprint-Specific Training Guidelines

Modes of sprint-specific training

Unresisted sprint training involves sprinting, either forwards of backwards, with maximal effort without the need for additional equipment. Unresisted sprinting is arguably the easiest training method to implement because all it requires is an open, flat, area with good traction. It is also one of the most effective methods for improving sprinting performance in youth (60). Adding a resistive stimulus to movement in a horizontal plane of motion is commonly referred to as resisted sprinting. Various training methods of resisted sprinting exist such as parachutes, weighted vests, belts, and mechanical pulley systems. However, the most commonly used and researched method of resisted sprint training is resisted sled sprinting (5). The two forms of resisted sled sprinting that exist are sled pulling and sled pushing, with both being popular in practice but with less research using the latter. Although sled pulling and pushing share many commonalities, many differences exist in relation to comparative size, shape, anatomical positioning, friction and force application which may in turn lead to changes in mechanics, load prescription and training (5). Figure 10.1 shows images of a female high-school 100 m sprint athlete performing a resisted sled pull and a resisted sled push. It is clear from comparing the four images that the two forms of resisted sprinting result in slightly different mechanics, most apparent being the elimination of the arm swing during sled pushing. However, both share certain traits related to body position and sprint posture; forward lean is increased during both conditions improving the orientation of the foot strike which could lead to increased horizontal impulse during resisted sprinting at heavier loads (5). As the external load increases, differences may appear dependent on the strength of the athlete. During sled pulling the waist belt can act as an external coaching cue to push the hips into extension, however excessive loading may lead to a break in the hips. Therefore, sled pushing may be favoured as a form of very heavy resisted sled sprinting over sled pulling.

[INSERT FIGURE 10.1 HERE]

Figure 10.1 A female high-school 100 m sprint athlete performing resisted sled pulls (top images) and sled pushes (bottom images) against a moderate load of 66% body mass (left images) and heavy load of 99% body mass (right images).

The individual characteristics of a young athlete, including size, strength, training history and maturation, may influence the ability to tolerate load and perform resisted sled sprints. For example, Rumpf et al. (47, 48) reported both acute and longitudinal differences in adaptation to resisted sled pulling between pre-PHV and post-PHV boys. Pre-PHV boys were slowed 50% more than post-PHV boys when pulling the same relative load (%body mass), and after 6 weeks of resisted sled training pre-PHV athletes showed no gains in performance in comparison to improvements in speed for boys post-PHV. Figure 10.2 provides an example of how strength and maturation may influence sled pushing mechanics. Both boys in Figure 10.2 are pushing the same heavy relative load of 100% body mass. The boy in figure A though is more mature and stronger and adopts a body position with much greater forward lean in turn altering the foot strike to favour horizontal force application. Conversely, the boy in panel B lacks the strength and maturity to maintain optimal sprint posture resulting at a break in the hips, which in turn negatively impacts the foot strike and likely diminishes the ability to apply horizontal force. From observation of Figure 10.1 load has an impact on the mechanics of the resisted sled sprinting; however, the primary influencer for young athletes appears to be strength and maturation. Young athletes who are more mature, have greater levels of relative strength and have a reasonable training age are likely to be able to manage higher resisted loads during resisted sprint training.

[INSERT FIGURE 10.2 HERE]

Figure 10.2 Two young athletes pushing a resistive load of 100% body mass but adopting different body positions.

Assisted sprinting is an advanced training method by which an individual performs supramaximal runs where they are exceeding their maximal running velocity; either by running down a sloped surface or being towed using a pulley or bungie system. Little is known about the effects of assisted sprint training in youth; therefore, we recommend it be used with caution. Practitioners should start by providing minimal assistance and exposure and progress both gradually while monitoring an athlete's ability to maintain form at supramaximal speed.

Frequency, Volume and Intensity

According to reviews of short-term sprint training studies in youth by Rumpf et al. (49) and Moran et al. (38), sprint-specific training sessions that lasted 8-10 weeks and comprised up to 16 sprints between 10 and 30 meters with a work to rest ratio of 1:25, or greater than 90 seconds, 2 to 3 times a week, with a total sprint volume of 240-480 m per session were most effective. The work to rest ratio allows for full recovery to ensure a maximal effort in each sprint, and practitioners should remember that more mature athletes will likely take longer to recover between efforts compared to less mature athletes. Monitoring sprint times within a session is one way to ensure each effort is maximal and that adequate recovery is being provided between sprints. Although the review work of Rumpf et al. (49) and Moran et al. (38) demonstrate that short-term interventions can be effective in improving sprint speed, practitioners are encouraged to take a longer-term, periodised approach to speed development in young athletes.

Progressive overload is a core principle for enhancing performance in any strength and conditioning programme. When implementing backward or forward running into a training mesocycle it has been shown that progressively increasing the number of high-intensity repetitions while concomitantly decreasing low-intensity repetitions promotes large improvements in performance (60). Therefore, it is recommended that sprint training be progressively overloaded with regards to running intensity and training volume. Figure 10.3 provides examples of progressive overload of total maximal sprint distance over 10 week training blocks during a general preparation phase and strength-speed phase. During the preparation phase, total sprint distance is the accumulation of athletes completing 8-10 repetitions of sprints 10-25 m in distance, although other lower intensity runs would also be completed. Progression follows a similar pattern during the strength-speed phase but with much shorter distances as athletes are pushing heavier sleds; in this example volume is the product of young athletes performing between 5-10 repetitions of heavy sled pushing over 7.5 m.

[INSERT FIGURE 10.3 HERE]

Figure 10.3 An example of progressively overloading total sprint volume across a 10 week block of unresisted sprinting during a general preparation phase, and a 10 week block of heavy sled pushing during a strength-speed phase of training.

The most commonly used method of load prescription for resisted sled sprinting is to apply load as a percentage of body mass. However, as commented on earlier and illustrated in Figure 10.2, the variation in strength, maturation and training age amongst young athletes can influence their ability to manage load during resisted sprinting, just as it would influence the ability to tolerate load during traditional resistance training. This means applying load as a percentage of body mass will provide an inconsistent stimulus across multiple athletes. Some athletes will be able to maintain speed relatively well with load, while other athletes will lose speed more quickly under load. A more appropriate way to prescribe load is to assess the individual load-speed relationship, as shown in Figure 10.4. Using this method, either sprint time or maximal velocity are measured in an unresisted sprint and in resisted sprints with increasing loads. The linear load-speed relationship can then be calculated to determine the rate at which load decreases velocity for a given athlete.

[INSERT FIGURE 10.4 HERE]

Figure 10.4 Individual load-speed relationships during sled pushing for two youth athletes (Adapted from Cahill et al., (5))

Figure 10.4 shows the load-speed relationship for two young athletes. The relationship is used to prescribe training that causes a predefined decrease in velocity, to provide a consistent training stimulus across athletes. For instance, it has been suggested that training with a resistance that decreases velocity by 50% will optimise power output (17). In Figure 10.4, Athlete B tolerates load less well than athlete A, if the goal is to train at a load that decreases velocity by 50% then Athlete A would need a load of 75% body mass and athlete B a load of only 50% body mass. Figure 10.4 shows four suggested training zones that could be used by coaches to target specific training adaptations using the load-speed method. Loads associated with a reduction in maximal sprint speed >65% can be categorised as strength-speed exercises, whereas loads associated with a 10-35% reduction in maximal sprint speed can be categorised as speed-strength exercises, and power falling between those two zones. A certain baseline level of strength (both horizontally and vertically) may need to be established before an athlete can truly utilise loads that optimise power (17). A training zone of technical competency in which speed is reduced by <10% could be used by coaches with the intention of adding a light loading stimulus without effecting sprint mechanics for sled pulling. At higher loads that create a decrease in speed >10%, resisted sprinting should be considered a specialised form of resistance training (5). The four training zones of technical competency, speed-strength, power and strength-speed may be associated with loads that are described as very light, light, moderate and heavy respectively.

Example Plan and Training Sessions

When implementing sprint-specific training into a young athlete's annual programme it is important to prescribe the appropriate exercises for the desired training adaptations. An example of an outline annual training plan is provided in Figure 10.5. The plan should be considered within the context of a comprehensive training programme that incorporates additional training complementary to speed development, together with other desirable training goals such as strength, power and agility development. Generally, it is recommended to work along a continuum from less intense and less specific to more intense and more specific training (21). During the general preparation phase, young athletes should be introduced to high-speed running via tempo training, while high-speed backward running may be incorporated to develop explosive strength with minimal stress on the knee joints (59). Heavier loading schemes for resisted sled sprinting could be used in preseason phases to emphasise developing maximum strength capabilities in a horizontal plane of motion. During the competitive season, high-intensity, low-frequency forward and backward sprinting may be used to maintain explosive capabilities, and subsequently, sprinting performance.

[INSERT FIGURE 10.5 HERE]

Figure 10.5 Example annual plan for speed training in youth athletes

If both sled pushing and pulling are available to the coach, it is recommended to use sled pushing during the strength-speed phases of training. This is due to the anterior positioning of the sled and use of the arms emphasizing a more horizontal strength training exercise than sled pulling. Moderate to lighter loads could be used closer to competition to develop power and augment speed-strength phases of training. This in turn would reduce the overall training load on the athlete entering the competitive phase. Regular testing of speed is included in the plan, both to inform training prescription and evaluate training effectiveness and. Testing speed is not only important for track athletes, but also those youth who compete in sports where speed is one of the important qualities that contributes to performance. The practitioner may choose to test more frequently during the strength-speed and speed-strength phases to monitor any changes in the load-speed relationship and adjust any resistance accordingly. Coaches could also use this approach to individualise load prescription to an athlete's force-velocity characteristics, identifying whether an athlete needs to better develop their force or velocity capabilities. With this approach the coach can prescribe load to match the training zone to the athlete's force-velocity characteristics (i.e. for an athlete who needs to improve their force rather than their velocity), which could result in better sprint training results compared to assigning the same resistive load to all athletes (17)

As youth mature, and their running form improves, they will be capable of running further at faster speeds (40). It is important to develop a young athlete's ability to maintain good running technique while running at high-speeds. Young athletes are capable of running at designated intensities (e.g. 50%, 70%, and +90% of max effort) using autoregulation (61). Performing running drills and using submaximal running (tempo running) can be used to develop technical competence prior to doing large volumes of maximal speed running. This is particularly important during the general preparation phases when young athletes might be returning from time away from sports and training, or long holidays. As per the example session shown in Table 10.3, less mature athletes, or those with a lower training age and lower levels of technical competency, should be introduced to basic sprint drills and use higher volumes of running at more moderate running speeds. Once an athlete is able to maintain good running form over all runs, the complexity of the sprint drill should be progressed and the volume of running at higher speeds increased (see Table 10.4). This type of structure will allow for developing motor coordination at increasing speeds and prepare their bodies for the demands of maximum velocity sprinting.

[INSERT TABLE 10.3 HERE]

Table 10.3 and Table 10.4 also provide example training sessions during the specific preparation phase with a focus on strength-speed work. Resisted sprints are used to improve sprint-specific strength qualities and coaches should differentiate loading schemes based on the maturation, competency and training age of the athlete. With less mature athletes or young athletes with lower competency and/or training experience of sprint-specific training, resisted sprinting can be used to provide a force stimulus but also to emphasise proper sprint mechanics. This can include a focus on body angle and forward lean using the waist harness and foot strike cues such as “push the ground away”. While inexperienced athletes are introduced to resisted sprinting with lighter loads, more mature athletes with good sprint competency and some training history can use heavy resisted sprints (Table 10.40. This type of training may suit more mature young athletes (e.g. mid and post PHV) as faster sprint times and the ability to generate higher relative horizontal forces naturally increase with advancing maturity and associated increases in strength (13, 40). When introducing heavy resisted sprinting, it is recommended that coaches first use sled pushing as young athletes are better able to maintain hip position and body and lower limb alignment pushing heavy loads as compared to pulling heavy loads.

KEY POINTS

- Speed naturally develops throughout childhood and adolescence. In childhood, boys and girls have similar sprint speed but with the onset of puberty boys improve their speed at a greater rate than girls
- Sprint speed naturally improves due to increases in stride length and not changes in stride frequency. With advancing age and maturity, youth maintain their ground contact time but travel further distance both when in contact with the ground and when in flight. These changes appear partly related to increases in relative propulsive force.
- A variety of non-specific training methods have been shown to transfer benefits to sprint speed in young athletes, including plyometric training, resistance training and combined training.
- Sprint-specific training should be used to develop speed using unresisted forward and backward running, resisted sprinting and possibly assisted sprinting. Coaches need to consider the maturity, competency and training age of young athletes to prescribe the most appropriate sprint-specific training programmes.

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Appendix 12 Acute Kinematics Effects of Motorized Assistance (JSCR Publication)

Appendix 12 comprises of the following published paper:

Clark KP, Cahill M, Korfist C, Whitacre T. (2019) Acute Kinematic Effects of Sprinting with Motorized Assistance. *J Strength Cond Res.* (Epub)

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ABSTRACT

Although assisted sprinting has become popular for training maximum velocity, the acute effects are not fully understood. To examine this modality, 14 developmental male sprinters (age: 18.0±2.5 years, 100m personal best: 10.80±0.31s) performed maximal trials both unassisted and assisted with a motorized towing device using a load of 7kg (9.9±0.9% body mass). Significant increases in maximum velocity (+9.4%, $p \leq 0.001$, $d = 3.28$) occurred due to very large increases in stride length (+8.7%, $p \leq 0.001$, $d = 2.04$) but not stride rate (+0.7%, $p = 0.36$, $d = 0.11$). Stride length increased due to small changes in distance traveled by the center of mass during ground contact (+3.7%, $p \leq 0.001$, $d = 0.40$) combined with very large changes in distance traveled by the center of mass during flight (+13.1%, $p \leq 0.001$, $d = 2.62$). Although stride rate did not demonstrate significant between-condition differences, the combination of contact and flight time was different. Compared to unassisted sprinting, assisted sprinting caused small but significant decreases in contact time (-5.2%, $p \leq 0.001$, $d = 0.49$) and small but significant increases in flight time (+3.4%, $p < 0.05$, $d = 0.58$). Sprinting with motorized assistance elicited supramaximal velocities with decreased contact times, which may represent a neuromuscular stimulus for athletes attempting to enhance sprinting performance. Future research is needed to investigate the effects of this modality across various assistive loads

and athletic populations, and to determine the longitudinal efficacy as a training method for improving maximum velocity sprinting performance.

Key Words: overspeed, maximum velocity, biomechanics, running performance

INTRODUCTION

Maximum velocity is highly correlated with performance in track & field (24) and many team sports (10, 18). Because of this, researchers and practitioners are continually searching for the most effective methods to enhance top speed. Assisted sprinting, commonly termed overspeed, is a popular mode of training where an external modality allows the athlete to run at speeds faster than can be achieved under normal unassisted conditions. Modes of assisted sprinting include running on a slight downhill slope (12, 23), training on a specialized high-speed treadmill (13), being pulled with a towing device such as elastic tubing (2, 4, 9, 19, 20, 22), a pulley system in conjunction with a body-weight supporting kite (15, 16), or a motorized cable (3, 25).

A primary reason for utilizing overspeed training is the belief that it may elicit longitudinal improvements in maximal velocity. Thus, the principle of training specificity suggests that acute increases in maximal velocity achieved during assisted sprints should be accomplished in accordance with known characteristics of faster running. These features include shorter ground contact times, reduced duty factors (ratio of contact time to total stride time), and larger mass-specific vertical forces (1, 5, 6, 7, 28, 29). Furthermore, it may be optimal to perform assisted sprints with modalities that minimize disturbances to the runner's natural gait. For example, prior research has demonstrated that when sprinting at maximum velocity during unassisted conditions, nearly all runners select gait mechanics that include flight times of 0.12 ± 0.01s and contact lengths (distance traveled by center of mass during ground contact) approximately equal to leg length (5, 28, 29). Theoretically, if assisted sprinting could acutely enhance maximum velocity via mechanisms normally observed with swifter running (decreased contact times and duty factors), and without causing other aberrant changes to the runner's normal gait, this mode of training may have potential to elicit long term improvements in top speed.

However, there is relatively little prior research on the acute effects of assisted maximum velocity sprinting using a towing device, and inconsistent modes and magnitudes of assistance have made it challenging to synthesize conclusions from the existing literature. A few prior studies have examined the effects on elastic band towing on performance and kinematics in the acceleration phase (2, 9, 22), but these investigations did not specifically examine maximum velocity. Other studies have examined maximum velocity sprinting with elastic bands using a towing force of 30-45 N (19, 20) or ~2-5% body weight (4). Mero & Komi (19) found increases in maximum velocity and stride length, with slight decreases in contact time and increases in flight time. DA Clark et al. (4) found increases in both maximum velocity and stride length and decreases in contact time that were most pronounced at tow force magnitudes of 3.8% and 4.7% body weight. Finally, a motorized towing system has been employed (3, 25) to elicit supramaximal increases in sprinting velocity from ~7-14%, with resulting kinematic changes such as decreased contact times, increased stride length, and increased stride rate.

Recently, a new towing device called the 1080 Sprint (1080 Motion, Lidingö, Sweden) has become popular for completing assisted sprints. The 1080 Sprint is an assistance/resistance cable device that uses a servomotor and accompanying computer software to control the load applied to the runner (see Methods). The 1080 Sprint allows for specific levels of force to be directly regulated by the user and provides a constant assistive pull to the runner during both ground contact and flight phases. Therefore, this mechanism may offer more precise control of assistance compared to other modes of overspeed sprinting. However, while the 1080 Sprint represents an impressive technological advance and is gaining in popularity as a training modality, the acute effects of assisted trials with this device are not conclusively understood.

Therefore, the purpose of this study was to investigate maximum velocity and kinematic stride parameters during assisted sprints with the 1080 Sprint. Based on the limited prior evidence on sprinting with motorized assistance (3, 25), our first hypothesis was that the assisted condition would elicit increases in maximal velocity and stride length, and decreases in ground contact time and duty factors. Because the 1080 Sprint applies an assistive force during both ground contact and flight phase, we predicted that this increase in total stride length would occur largely due to increases in center of mass distance traveled while airborne (flight length). Furthermore, while decreases in ground contact time could potentially lead to increases in stride rate, prior research has not demonstrated significant increases to flight time during sprinting with motorized assistance (3, 25). Therefore, our second hypothesis was that there would be no significant changes in flight times or stride rates in the assisted conditions.

METHODS

Experimental Approach to the Problem

To evaluate the research question and test the hypotheses, analysis of the maximal velocity phase during full-effort sprints was used to determine the spatial and temporal kinematic changes elicited by sprinting with motorized assistance. A within-subject study design was employed during a single testing session, with subjects sprinting under both normal (unassisted) conditions and while assisted with the 1080 Sprint. The primary outcome variables of interest were sprinting velocity, ground contact and flight time, contact and flight length, stride rate and stride length, and calculation of the duty factor ratio.

Subjects

14 male developmental sprinters volunteered and provided written informed consent in accordance with the local institutional review board, including parental consent for subjects under 18 years of age. Subject characteristics are listed in Table 1, including age, height, mass, and self-reported personal best in the 100m dash. All subjects were healthy and regularly performing sprint training (minimum twice per week) at the time of the testing, but none had prior experience completing assisted sprints using the 1080 Sprint. These developmental sprinters were recruited to participate because they were considered likely to possess the base levels neuromuscular power and sprinting technique necessary for the safe and effective completion of the experimental testing protocol.

***** Table 1 near here *****

Procedures

All testing took place on a rubberized indoor track with a 60m straightaway. First, subjects were measured for height and body mass. Next, subjects performed a standardized fifteen-minute warm-up including jogging, skipping, dynamic stretches, and submaximal sprints (similar to dynamic warm-up in reference 26). Following the warm-up, subjects completed four 60m sprints in two different conditions: the first two repetitions while sprinting without assistance, and the next two repetitions while sprinting with assistive force from the 1080 Sprint. Because it was expected that the subjects would be sprinting at supramaximal speeds during the assisted sprints, a randomized order was not employed, and the two unassisted sprints were performed before the two assisted sprints to ensure that the subjects were completely prepared for the demands of supramaximal sprinting. For each trial, subjects lined up at the starting line in an upright 'two-point' stance with the preferred leg forward and started at their own initiative. They were instructed to accelerate maximally to approach top speed by 20m, to sprint at top speed from 20-40m, and to decelerate from 40-60m. Split times were measured from 20-30m and 30-40m. Subjects were allowed complete recovery and rested a minimum of six minutes between trials.

During assisted trials, subjects sprinted while wearing a waist harness connected to the 1080 Sprint composite fiber cable, which is wrapped around a spool and extends up to 90 meters in length. The cable pulled the subjects from the front with a load controlled via a servomotor (2000rpm G5 Series Motor, OMRON Corp., Kyoto, Japan) and accompanying Quantum computer software (1080 Motion, Lidingö, Sweden). During the trials, the 1080 Sprint device was set at a height of 1m to ensure that it was pulling the runners with a directly horizontal assistive force. The 1080 Sprint allows the load to be adjusted from 1-15kg, and all subjects in this investigation were pulled with an assistive load of 7kg. This load was selected because the investigators' prior experience indicated that subjects of similar physical profile (i.e., high school and collegiate sprinters) could complete assisted trials using this assistive load with minimal observable changes to gait mechanics, and because previous research utilizing similar levels of assistance had demonstrated substantial increases in maximal velocity (3, 25). Per manufacturer recommendations, all trials using the 1080 Sprint were completed in the Isotonic mode. The Quantum software calculates the distance traveled by the sprinter and was programmed to terminate the assistive load at the 40m line, allowing the sprinter to decelerate safely after the maximum velocity portion of the sprint was completed. The 1080 Sprint device, and a subject completing an assisted trial using the 1080 Sprint, are depicted in Figure 1.

***** Figure 1 near here *****

All subjects wore their own athletic clothing and athletic shoes (track spikes) to complete the trials; since subjects served as their own controls, this was not viewed as a confounding variable. Body mass was measured using a digital scale (Supac Model EB-8008, Shanghai, China). Split times were measured with an automatic dual beam timing system (Swift Speed Light, Wacol, Australia), as dual beam systems have increased accuracy over single beam systems that do not use signal processing mechanisms (11). Sprinting mechanics were recorded using a high-speed video camera (Sony rx100 iv, Sony USA, New York, NY) filming at 960 frames per second. The camera was placed on a tripod at a height of 1.0 meter and at a perpendicular distance from the running lane of 6.0 meters, and panned on the runner to ensure that all strides in the 30-40m zone were recorded. The experimental set-up is illustrated in Figure 2.

***** Figure 2 near here *****

Average maximum velocity was determined from 30-40m split time. Split times from the 20-30m zone and 30-40m zone were compared to ensure that the runner had reached near maximum velocity by the 30-40m zone (see Results). The fastest unassisted sprint (trial one or two) and the second assisted sprint (trial four) were analyzed. The first assisted sprint (trial three) was used to familiarize the subjects to sprinting with the 1080 Sprint and thus was not included in the kinematic analysis. Before trial three, subjects were fitted with the waist harness and briefly reminded that the 1080 Sprint was going to pull them with an assistive force during the sprint; no other physical familiarization was completed prior to trial three. Kinematic stride parameters in the 30-40m zone were quantified by reviewing the video in Quicktime version 7.7.9 (Apple Software, Cupertino, CA). Contact times and flight times were determined by counting frames and dividing by the known recording rate of 960 frames per second. Two of the investigators independently analyzed the videos to determine the reliability of this method (see Results). Contact time was defined as all frames when the sprinter's foot was clearly touching the ground. Flight time was defined as all frames when the sprinter had neither foot in contact with the ground. Four contact phases and four flight phases in the 30-40m zone were evaluated, and the average of these times was used in the statistical analysis.

Stride time (t_{stride}) was defined as the average time to complete one ground contact (t_c) and one flight phase (t_f). Stride rate ($rate_{stride}$) was defined as the inverse of stride time. The duty factor ratio represents the period of a gait cycle in which one foot is on the ground, and was defined as contact time divided by total gait cycle time (sum of two contact phases and two flight phases). Stride length (L_{stride}) was defined as the distance covered between consecutive ground contacts on contralateral feet, and was calculated as average velocity divided by stride rate ($rate_{stride}$). Contact length (L_c) was defined as the horizontal distance traveled by the center of mass during the ground contact phase, and was calculated as the product of average velocity and ground contact time (t_c). Flight length (L_f) was defined as the horizontal distance traveled by the center of mass during the flight phase, and was calculated as the product of average velocity and flight time (t_f).

The equations for these variables are listed below in Equations 1-6:

t_{stride} (s) = $t_c + t_f$ *(Equation 1)*

$rate_{stride}$ (strides • s^{-1}) = $\frac{1}{t_{stride}}$ *(Equation 2)*

duty factor (ratio) = $\frac{t_c}{2 \bullet (t_c + t_f)}$ *(Equation 3)*

L_{stride} (m) = $\frac{avg.\ velocity}{rate_{stride}}$ *(Equation 4)*

L_c (m) = avg. velocity • t_c *(Equation 5)*

L_f (m) = avg. velocity • t_f *(Equation 6)*

***** Figure 3 near here *****

Statistical Analyses

Between-condition (unassisted vs. assisted) differences were evaluated with separate dependent *t*-tests on each variable, using a statistical significance level of 0.05. Additionally, percentage change and effect size statistics *d* (8) were utilized to determine the magnitude of difference between unassisted and assisted conditions. Percentage change between conditions for all variables was calculated as: {(assisted – unassisted)/(unassisted)} • 100. Effect size statistics were calculated as the difference between group means divided by the pooled standard deviation. Threshold values for *d* statistics were as follows: < 0.20 (trivial), 0.20 – 0.60 (small), 0.61 – 1.20 (moderate), 1.21 – 2.00 (large), and 2.01 – 4.00 (very large) (14). All statistics were completed using Microsoft Excel.

RESULTS

Mean split times demonstrated minimal difference between the 20-30m zone and 30-40m zone for both the unassisted trials (1.02 ± 0.03 and 1.01 ± 0.03s, respectively) and the assisted trials (0.94 ± 0.02 and 0.92 ± 0.03s, respectively). These results indicate that in both unassisted and assisted conditions, the sprinters had reached near maximum velocity by 30m and were undergoing only ~2% net velocity increase in the 30-40m zone. With regards to determination of contact time and flight time from video analysis, a total of 224 contact and flight phases were analyzed (14 subjects x 2 trials per subject x 4 contact phases and 4 flight phases per trial). Across the 224 contact and flight phases, the inter-rater reliability between the two investigators was high (Pearson's r = 0.983) and the inter-rater mean absolute difference was less than 0.002s.

The assistive load of 7kg on average represented 9.9 ± 0.9% of the subjects' body mass. Compared to the unassisted condition, all 14 subjects demonstrated an increase in maximum velocity, and the group mean increase in 30-40m velocity in the assisted condition was 9.4 ± 1.5%. Dependent t-tests revealed significant between-condition differences for maximum velocity, contact time, flight time, duty factor, stride length, contact length, and flight length. There were no significant between-condition differences for stride time or stride rate. Group mean results for unassisted vs. assisted conditions are listed in Table 2.

***** Table 2 near here *****

Individual results for unassisted vs. assisted conditions are illustrated in Figures 4 through 6. Figure 4 presents individual results for maximum velocity (Fig. 4A) and duty factor (Fig. 4B). Figure 5 presents individual results for the temporal parameters of contact time

(Fig. 5A), flight time (Fig. 5B), and stride rate (Fig. 5C). Figure 6 presents individual results for the spatial parameters of contact length (Fig. 6A), flight length (Fig. 6B), and stride length (Fig. 6C).

***** Figure 4 near here *****

***** Figure 5 near here *****

***** Figure 6 near here *****

DISCUSSION

Our hypotheses were generally supported, as faster maximum velocities in the assisted condition were achieved primarily through significantly increased stride length and decreased contact times and duty factors. Somewhat counter to our expectations, this occurred in combination with slightly longer flight times and contact lengths. Comparing results across subjects, the changes that occurred during assisted sprints were very consistent for the variables of maximum velocity, duty factor, and contact time. All 14 subjects increased maximum velocity in the assisted condition (Fig. 4A), and 13 out of 14 subjects achieved this increase in maximum velocity via decreased duty factors (Fig. 4B) and decreased contact times (Fig. 5A).

For the variable of flight time, there was some irregularity among subjects between conditions. 10 of the 14 subjects showed increases in flight time, with 8 of these 10 demonstrating more than a 5% increase in flight time (Fig. 5B). For the variables of stride time and stride rate, there was very little change between conditions across all subjects. Although some subjects demonstrated very minor increases in these variables while others demonstrated minor decreases, all 14 subjects had less than 5% absolute difference in these variables across conditions (Fig. 5C and Table 2). Additionally, the results were very consistent across subjects for the variables of contact length, flight length, and stride length. 13 out of the 14 subjects demonstrated increases in contact length, although for 11 of the subjects these changes were less than 5% (Fig. 6A). For flight length and stride length, all 14 subjects demonstrated increases in the assisted condition, and 13 subjects demonstrated increases in 8% or greater for flight length and 5% or greater for stride length (Fig. 6B and 6C). During assisted conditions, only one sprinter (Subject #5) demonstrated increases in flight length and stride length of less than 2%.

The increases in assisted maximum velocity in this study are comparable to other studies using motorized towing devices (3, 25). In the present study, a mean increase in maximum velocity of 9.4% occurred using a towing load equivalent to 9.9% of mean subject body mass. Sugiura & Aoki (25) found a mean increase in assisted maximum velocity of 7.5% using a 5kg towing tension that was equivalent to ~7.1% of mean subject body mass, and Bosco & Vittori (3) found a mean increase in assisted maximum velocity of ~14% using a 100-150N towing force that was equivalent to ~15-22% of mean subject body mass. With regards to kinematic spatial and temporal parameters, other studies have found increases in stride length ranging from ~3-8.5% (3, 19, 20, 25) and decreases in contact time ranging from ~6-8.5% (3, 19, 25), which are similar to the findings in the present study.

The increase in stride length found in this study was primarily caused by an increase in flight length rather than an increase in contact length. It was expected that flight length would increase because the 1080 Sprint provides assistive force while the runner is airborne. However, before undertaking the study, it was unknown whether the assisted condition would also elicit increases in contact length. Prior research has demonstrated that during unassisted conditions, runners typically utilize contact lengths that are slightly longer than leg length (5, 28, 29). Conceivably, to handle the faster speeds during assisted trials, subjects could have substantially increased contact length by increasing leg touchdown or leg takeoff angles (i.e., foot further in front of center of mass at touchdown or foot further behind center of mass at takeoff). Although joint angular kinematics were not directly measured in this study, analysis of contact length metrics can provide insight into ground contact geometry in unassisted and assisted conditions. If large increases in contact length had occurred in the assisted condition, this would indicate that the subjects made major (and possibly detrimental) modifications to their ground contact mechanics. However, while the mean increase in contact length was statistically significant, the magnitude of change was small, implying that radical changes to ground contact geometry were not generally observed.

There were no significant between-condition differences in stride time or stride rate. However, there were small but significant decreases in contact time and small but significant increases in flight time. Therefore, the duty factor decreased when the subjects sprinted with assistance, which agrees with several other prior studies (3, 4, 19, 25). Furthermore, decreased contact times and duty factors implies that the vertical support forces must be applied to the ground at a faster rate during the assisted condition, which may be an important consideration for transfer to longitudinal improvements in maximum velocity. Weyand et al. (29) found that it was not just the amount of mass-specific vertical force that subjects could apply to the ground, but also how rapidly this force could be applied, that determined top speed across various locomotor gaits (forward running, backward running, and one-leg hopping). Recent research on sprinting with body-weight support kites (15, 16) has indicated that this modality allows for decreased ground contact times during top speed sprinting. These authors suggested that the body-weight support kite system could elicit a beneficial training effect due to the stimulus provided when sprinting with decreased ground contact times (15, 16). Similarly, training modalities such as assisted sprinting with the 1080 Sprint may represent a positive neuromuscular stimulus that could have a longitudinal benefit on maximal velocity due to the requirement of applying vertical support forces in briefer contact times.

With respect to the population examined in this study, the fact that subjects had no prior experience performing assisted sprints with the 1080 Sprint could potentially have been a limiting factor. Instead, the results suggest that athletes with this physical profile and sprint training background habituate quickly to assisted sprinting, and may not need an excessive number of repetitions to become accustomed to the 1080 Sprint. Indeed, the subjects in this study completed one familiarization repetition (trial three) to become habituated to assisted sprinting with the 1080 Sprint, and this seemed to be sufficient to allow for large increases in acute maximal velocity during trial four including beneficial decreases in ground contact time. Whether looking at between-condition results across the group as a whole (Table 2), or examining the results across the individual subjects (Figures 4-6), it can be concluded that the adjustments to the enhanced velocity were generally achieved with assisted sprinting was attained via mechanisms that are consistent with faster running speeds.

Although this study yielded useful insight into assisted sprinting with the 1080 Sprint, several aspects remain unresolved. First, future studies need to examine whether the results of this investigation generalize to other populations (such as females, team sport athletes, elite sprinters) or to runners who have trained extensively with the 1080 Sprint. Furthermore, more research is required to determine the acute effects of a range of assistive loads, and to determine if interactions exist between the assistive load and the population being investigated. Perhaps the most important question is whether completing assisted sprints with the 1080 Sprint can have a beneficial effect on performance longitudinally as a training modality. The limited prior research on the longitudinal effects of assisted sprint training have not provided definitive conclusions (17, 27), and clearly additional training studies are necessary to answer these questions.

PRACTICAL APPLICATIONS

This investigation examined the acute kinematic effects of assisted sprinting. 14 developmental male sprinters ran maximally both unassisted and while assisted with the 1080 Sprint, being pulled with a load equivalent to approximately 10% body mass. Results demonstrated that acute increases maximum velocity of nearly 10% were achieved via greater stride length, but not stride rate. However, although stride rate did not change, there were small but significant decreases in contact time and increases in flight time, indicating a decreased duty factor ratio during the assisted conditions. This represents a requirement to apply vertical support forces to the ground at a faster rate, which could serve as a beneficial neuromuscular stimulus if used consistently during training. Although additional research is clearly necessary to investigate the efficacy of assisted sprinting with the 1080 Sprint as a longitudinal mechanism for increasing top speed, coaches and practitioners working with developmental sprinters can use the results from this study as a foundation to prescribe loads for assisted sprinting. Furthermore, this study demonstrates that sprinting with motorized assistance may be a valuable tool for strength and conditioning coaches that are looking for modalities to decrease ground contact times during maximal velocity training.

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Figure Captions

Figure 1. A representative subject completing an assisted trial with the 1080 Sprint providing assistive force via a waist harness (Fig. 1A), and a photo of the 1080 Sprint (Fig. 1B).

Figure 2. Schematic diagram of the experimental testing set-up.

Figure 3. Diagram of the variables of Contact Length, Flight Length, and Stride Length.

Figure 4. Individual subject results in unassisted vs. assisted conditions for Maximum Velocity (Fig. 4A) and Duty Factor (Fig. 4B).

Figure 5. Individual subject results in unassisted vs. assisted conditions for the temporal parameters of Contact Time (Fig. 5A), Flight Time (Fig. 5B), and Stride Rate (Fig. 5C).

Figure 6. Individual subject results in unassisted vs. assisted conditions for the spatial parameters of Contact Length (Fig. 6A), Flight Length (Fig. 6B), and Stride Length (Fig. 6C).

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