Force-Velocity Profiles and Optimal Loads During Sled Towing in Rugby Players

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Abstract:

Recent research has focussed on improving and developing on-field sport-specific measurement technologies and methodologies to enhance sprint performance. As a result of this, resisted overground sprinting has gained popularity recently as both a training method and sprint assessment method. Researchers and strength and conditioning coaches have paid particular interest to the ability to profile athletes force-velocity (F-V) capabilities using sled resisted overground sprinting. This information can be used to determine the optimal training load for maximal power output. However, this has only been investigated in a limited number of sporting cohorts, primarily recreational and sprint-trained athletes. The aim of this thesis was two-fold, 1) to evaluate current sled tow research focussing specifically on the technologies and methodologies currently used to assess sprint performance in field-based sports, and 2) to provide initial benchmark information for strength and conditioning coaches on positional demands for semi-elite male rugby union players using the newly introduced instrumented sled as the sprint assessment tool. Chapter 2 presents a narrative review of the current sled tow literature in court and field-sport athletes and highlights the need for research that streamlines methodological approaches. The review draws attention to the need to provide new and updated technology that can accurately assess sprint performance variables within a range of sporting cohorts. Consequently, chapter 3 presents a relatively new sprint assessment tool being an instrumented sled and which was used to determine the F-V and power-velocity (P-V) relationships within male rugby union players. The accuracy of the instrumented sled to measure sprint performance variables was determined by fitting the F-V relationship with linear regressions and the P-V relationship fitted with polynomial quadratic regressions (second-order), with both relationships being near perfect (F-V: R^2= 0.983, P-V: R^2= 0.986). Subsequently, chapter 4 compared sprint performance variables measured from the instrumented sled by position (forwards vs. backs) within semi-elite male rugby players. The research found there to be significant positional differences between the forwards and backs for F0 ($P \leq$ 0.02, ES= -0.75, %difference= 12.4%) and Pmax values ($P \leq$ 0.01, ES= 0.82, %difference= 8%) with forwards displaying more force dominant profiles than backs. These differences were likely influenced by physical attributes and positional demands. Relative to body weight the optimal loads on average were 55.87%BW for the forwards and 61.1%BW (ES=0.37) for the backs. This result is important to note as it highlights how individualised optimal loading is to not only each sporting cohort but also to the positional groups within each sport. Given the promising results of these early studies using the instrumented sled, strength and conditioning coaches and researchers should consider the use of such technology as an accurate sprint performance assessment and training tool.

Table of Contents:

List of Figures:

List of Tables:

List of Appendices:

Attestation of Authorship:

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

Chapters 2 through to 4 represent three individual manuscripts that have either been submitted or in preparation to be submitted to peer-reviewed journals for publication. My contribution to these works as well as the various co-author's contributions are outlined on the following pages. All co-authors have approved the inclusion of joint work within this master's thesis.

Signed: ____________________

Date: 22 July 2021

Candidate Contributions to Co-authored Publications

The student was the main contributor of the research in this thesis to the minimum requirement of 80%. The student was also the main contributor to the writing of ethics applications and necessary progress reports for the completion of the thesis.

Chapter 2.

Earnshaw, K., Brughelli, M., Uthoff, A. Evaluating Methodology and Technology of Sled Tow Studies in Field Sports Athletes: A Narrative Review.	Earnshaw, K. (85%) Brughelli, M. (5%) Uthoff, A. (10%)

Chapter 3.

Earnshaw, K., Brughelli, M., Uthoff, A., Tinwala, F. Accuracy of an Instrumented Sled to Measure Force-Velocity and Power-Velocity Outputs of Male Rugby Union Players During Sled Towing. using an instrumented sled.	Earnshaw, K. (85%) Brughelli, M. (5%) Uthoff, A. (5%) Tinwala, F. (5%)

Chapter 4.

Earnshaw, K., Brughelli, M., Uthoff, A., Tinwala, F. Force-Velocity Profiles and Optimal Loads of Male Rugby Players by Position in Over-Ground Sled Sprinting	Earnshaw, K. (85%) Brughelli, M. (5%) Uthoff, A. (5%) Tinwala, F. (5%)

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Ethical Approval

Ethical approval to undertake this research was granted by the Auckland University of Technology Ethics Committee (AUTEC; #20/345) on 26 November 2020 (Appendix 1.).

Because this thesis was to include subjects contracted to New Zealand Rugby (NZ Rugby), ethical approval was granted by Medicine and Science Advisory Panel (MSAP) on 3 May 2021 allowing research using NZ Rugby athletes to be published (Appendix 2.).

Chapter 1:

INTRODUCTION AND RATIONALE

BACKGROUND:

An important performance aspect of field sports such as rugby, hockey, and soccer is the ability to generate high power output to increase sprint performance.[39] Often in field sports, athletes do not have the opportunity to reach true peak velocity before being interrupted, therefore, the focus of strength and conditioning has shifted towards sprint acceleration and horizontal force development through resistance training methods.[39] The use of towing weighted sleds while sprinting has become increasingly popular as a means to develop acceleration and horizontal force.[12,39,63] Current acute sled tow research has identified a direct linear relationship between increased sprint time with increasing load.[40] Longitudinal studies have seen improvements in the early acceleration phase of sprinting as a result of resisted sled tow training.[40] Loads that are <30%BM are considered to be light loads, while loads >30%BM are considered to be heavy.[15] The review by Alcaraz, Carlos-Vivas, Oponjuru, and Martínez Rodríguez[40] suggests that resisted sled towing with 'light' (<10 %Body Mass [BM] or <10 %Velocity decrement [Vdec]) loads had 'small' acceleration decreases of -1.5 % to 'moderate' in maximal sprint velocity in sprint trained athletes, suggesting that lighter loads may be beneficial for maximal velocity training.[40] In contrast, Tillar, Teixeira, and Marinho[63] found there to be no effect on sprint performance after utilising resisted runs in male field sport athletes when resistance weight was <10%BM.[63] This may suggest that there is minimal effect on sprint performance characteristics when sled tow load is <10%BM for field sport athletes. Current recommendations in the literature suggest that light loads are suited for maximal velocity improvements (speed-strength) and heavier loads are better suited for acceleration phase improvement (strength-speed).[12,40] Further to this, it is important to understand an athletes' optimal load for power output in order to prescribe the appropriate load for the position-specific strength quality wanted. As the F-V characteristics are expressed differently for each individual, the load needs to be specific to the individuals' strengths and weaknesses.[12,40,65]

Often athletes undergo force-velocity (F-V) profiling to identify peak power and determine dominance in either force or velocity which in turn can influence programming. F-V profiling includes several different characteristics, such as theoretical maximal horizontal force production, theoretical maximal running velocity, the slope of the F-V relationship, and maximal power output.[64] The F-V relationship is important in determining individual capabilities and identifying deficiencies in either force production, the direction of force applied, or running velocity.[3] F-V profiling is beneficial in aiding the development of programming, as it provides an in-depth understanding of the required stimulus to generate an optimised power production for specific sprint phases. In relation to sled towing, F-V profiling has been validated during overground sprinting from an equation that uses the time and distance of the sprint.[45] Further to this, the F-V and P-V relationships have been accurately profiled using regular sled towing equipment during overground sprinting for a range of athlete cohorts.[12] Recent research into horizontal F-V profiling has determined that the relationship between sprint performance and maximal horizontal force production decreases as the sprint distance increases, suggesting that horizontal force production is highest during the acceleration phase of sprinting.[64] Recent research results also suggest that the orientation of force application increases horizontally as sled load increases indicating that heavier sled loads allow for increased horizontal force application.[3] This study required the use of five cameras and a validated method using velocity-time data to estimate F-V and power-velocity (P-V).[3] To date research has yet to investigate F-V characteristics in a range of different populations using updated modernised technologies as research has primarily focussed on sprint-trained athletes.

Sprint acceleration is influenced by both force and velocity with literature focussing heavily on force. To better understand how sled tow loading can be used to optimise power production, changes in velocity during resisted sprint should be further investigated. The acute effects of sled tow loads on velocity were researched by Elmontassar, et al.[50], who looked into the impact of sled loads of 7%, 10%, 15%, and 20% of body mass (BM) on velocity over 15m. It was found that as weight increased, velocity decreased, which aligns with known relationships. From this information, the research team was able to develop an equation to prescribe resisted training loads for sprinters.[40,50] However, this study used sprint athletes from starting blocks and only measured performance up to 15m using relatively light loads; therefore, the results may not be applicable to field sport athletes who may wish to enhance force production capabilities associated with heavier sled loads.[50] The understanding of the relationship between sled tow loading and velocity across all load levels, and over acceleration split phases is worthwhile exploring as this may enable more precise programming for musculotendinous adaptations resulting in changes to sprint acceleration F-V characteristics.

Sled tow research has also recently expanded into which method of load prescription should be used. A method investigated and commonly used to prescribe sled load to optimise programming and power output is velocity decrement (VD).[15] This method uses F-V profiling to identify areas of improvement and guides the prescription of sled tow load based off of an individual's velocity decrement when focussing on maximising power during a weighted sprint. However, this method of prescription is not of use unless velocity or split times can be assessed, and therefore, there is a need for increased research and a deeper understanding of the different methodologies and technologies used to determine sled load prescription.

The proposed thesis is set to bring current sled tow research together to highlight what is known and highlight the current gaps that exist. The research looks to compare F-V profiles and optimal loads between backs and forwards within the male rugby population, utilising an instrumented sled, as well as, looking to determine construct validity of an instrumented sled within the male rugby population. The information from such research will expand upon current research by providing additional benchmark instrumented sled tow data that may help guide coaches with load prescription.

SIGNIFICANCE & PURPOSE:

This thesis aims to collate and review the current literature around sled towing and F-V profiling in field sports. It is important when undertaking sprint assessment that the method of testing mimics sport-specific application as closely as possible, therefore, the use of an instrumented sled is a significant step towards sport-specific sprint assessment for field-sport athletes. The ability to profile F-V within the field with an instrumented sled would be highly beneficial to strength and conditioning coaches as it is minimally disruptive to training while providing the necessary sprint assessment information for programming.

Due to the line of investigation surrounding the use of an instrumented sled as a sprint assessment tool, a clinimetric methodological approach was adopted as a partial framework for the thesis. The clinimetric approach focuses on four main fundamental properties within physiological and performance testing; accuracy (see Chapter 3), reliability, discriminative ability (see Chapter 4), and sensitivity to change.[72] This ensures that a high standard of rigor is held when proposing the use of a novel method of sprint assessment.[72] This approach aims to provide the initial steps for the assessment of an instrumented sled as a novel method of sprint assessment.

THESIS AIM:

The specific aims of this thesis were to:

1) Evaluate the current methodologies used in sled tow research on field sport athletes.

2) Evaluate the current technologies used in sled tow research on field sport athletes.

3) Determine the accuracy of the force-velocity and power-velocity relationships using an instrumented sled.

4) Compare the force-velocity profiles and optimal loads of male rugby players by position.

THESIS STRUCTURE & FORMAT:

The thesis follows the pathway two format (manuscript structure) where the thesis is comprised of a series of stand-alone chapters that are prepared for peer-reviewed publication (Figure 1). The thesis is structured to include an overall thesis abstract, Introduction (Chapter 1), narrative review (Chapter 2), and two experimental studies (Chapters 3 & 4), followed by a chapter that summarises the main research points and provides an overall conclusion, practical applications, and direction for future research (Chapter 6). Due to the thesis being formatted for publication each chapter is written as its own body of work with chapters 2, 3, and 4 written for the purpose of publication as its own individual manuscript, and therefore, recurring themes and information are present across multiple chapters. The thesis follows an APA reference style adopting the numbering system for in-text references.

Chapter 2: A narrative review that focuses on the methodological and technological assessment tools utilised in sled tow research and practice within field sport athletes. The review discusses and highlights the current technologies used to assess sprint performance, the methodologies used to determine sled tow loading, their influence on performance outcome variables, and their use in resisted sprint training prescription. This chapter identifies the existing gaps in sled tow research and therefore provides a base for the following experimental chapters.

Chapter 3: The first experimental study investigated the accuracy of the instrumented sled (i.e., construct validity) by assessing the goodness of fit of the F-V and P-V relationships within semi-elite male rugby players. This chapter was necessary to follow the clinimetric approach to assessing the instrumented sled as a measurement tool for sprint performance variables. This study provided needed confidence in its ability to accurately assess sprint performance variables providing sound grounds for the subsequent chapter 4.

Chapter 4: This study builds on chapter 3 and the clinimetric framework for assessment of the instrumented sled by investigating the sled's discriminative ability. The study sought to compare F-V profiles and optimal loading between positions in a larger sample group of semi-elite male rugby players.

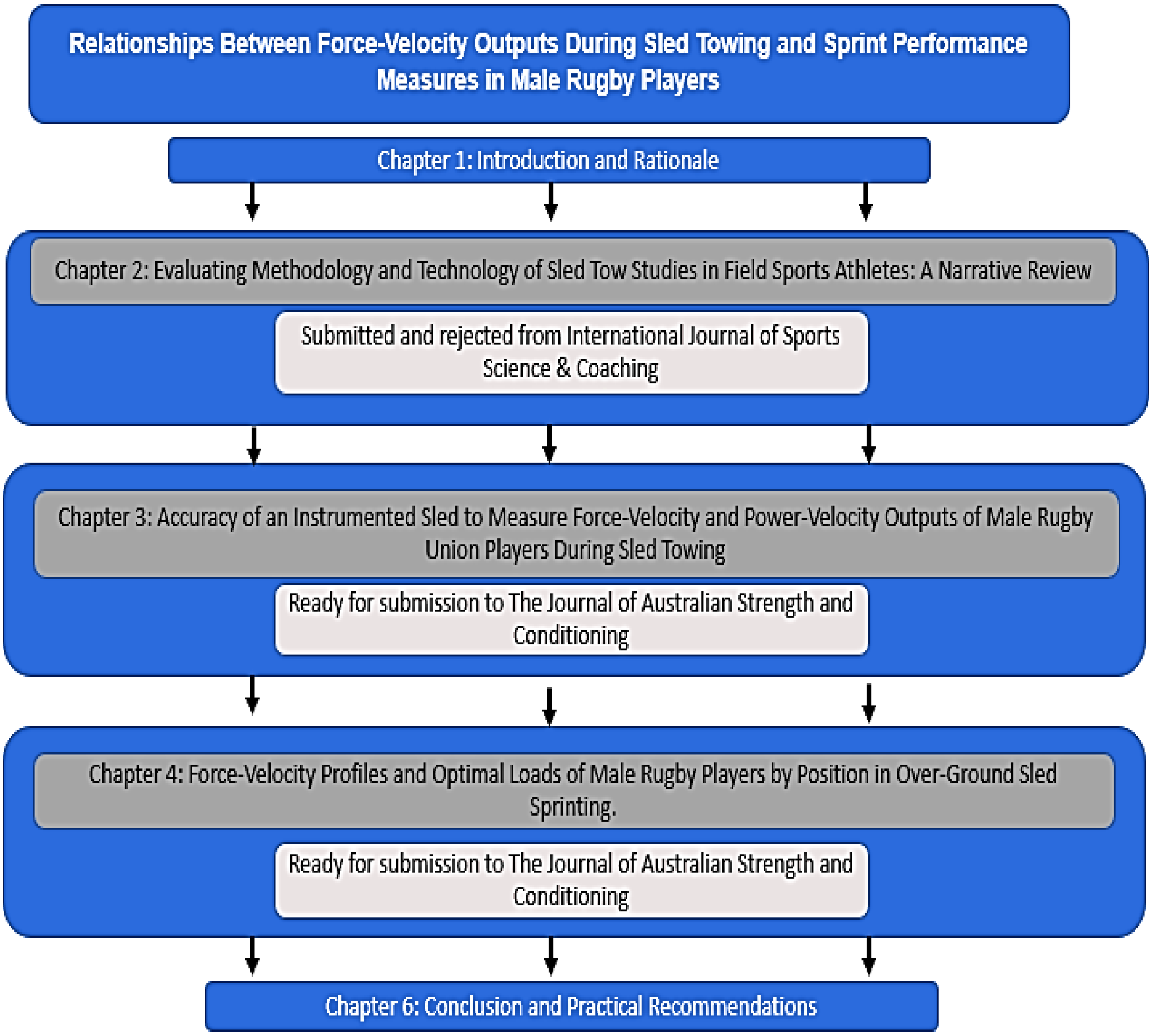

Figure 1. Thesis structure outline.

Chapter 2:

Evaluating Methodology and Technology of Sled Tow Studies in Field Sports Athletes: A Narrative Review

Prelude:

This chapter focuses on evaluating the various methodologies and technologies used across sled tow literature relevant to court and field-based sports. A number of methodologies have been used within sled tow research. This review compiles and evaluates such methodologies drawing attention to their effect on outcome variables. The review also presents and critiques an array of technologies used within strength and conditioning to assess sprint performance. The benefits and limitations of each technology and the performance variables measured are highlighted. This chapter was purposeful in identifying current gaps and areas of improvement for future research and application in chapters 3 and 4.

Abstract:

The use of resisted sled towing to enhance sprint capabilities has become one of the most common forms of training in the past decade due to its ability to develop phase-specific mechanical and muscular sprint capabilities. The increase in sled tow popularity has resulted in an abundance of literature highlighting discrepancies around load prescription volume, intensity, and methodology. To date, sled tow reviews have focussed on the usefulness of sled tow as a form of resisted sprint training in comparison to unresisted sprint training. The purpose of this review is to review the different technologies and methodologies used to assess sled tow sprinting and their associated performance variables and provide practical takeaways for coaches utilising this method of training. The most common technologies currently used to assess sled tow sprints include radar and dual-beam timing light systems. Literature suggests velocity decrement is the preferred loading method to target individual differences and provide sufficient individual athlete overload stimulus, however, ongoing debates have led to alternative methodologies being explored. Research has detailed kinetic and kinematic variable relationships with increasing loads, and how these relationships, in conjunction with force-power-velocity profiling variables, are used to guide programming. This review outlines current sled tow literature methodological approaches, with an emphasis on how different technologies and application of methodology used effects outcome variables. Furthermore, it aims to assist current understandings of sled tow application, highlighting a need for future research to streamline methodological approaches and develop technological advances to accurately measure and report sprint performance variables.

1. INTRODUCTION:

Sprint performance is a fundamental capability for success in field sports.[1] Resistance training exercises are commonly used to improve sport-specific sprint performance capabilities.[2] Due to the nature of field sports, resisted sprinting has become a popular method amongst strength and conditioning coaches to improve sprint performance due to the ability to overload the athlete while adhering to the principle of specificity.[1,2,3,4] Common forms of applied resistance sprinting include sled tows, parachutes, resistance bands, and weighted vests.[8] Sled towing has become an increasingly popular method of resisted sprinting due to the ability to develop horizontal force output, appropriately overload an athlete, and maintain/replicate specific sprint motor patterns.[9] Resisted sprint testing can allow strength and conditioning coaches to assess and profile individuals' force-velocity (F-V) capabilities. The variables that testing often looks to assess and characterise F-V capabilities include theoretical force and velocity production as a result of resisted sprint training.[3] Resisted sprinting improves sprint maximum force output (Fmax), theoretical maximum force (F0), theoretical maximum velocity (V0), and maximal power output (Pmax).[3] F0 and Fmax are linked to the initial acceleration phase (0-5 m), V0 is linked to the maximal velocity an athlete can produce in the absence of mechanical resistances, and Pmax is the ability of the athlete to produce the maximal combination of F0 and V0 throughout the acceleration phase.[3]

Using an athlete's F-V profile allows coaches to monitor changes to the F-V performance variables through increasing neural activation, recruitment of high-threshold motor units, and horizontally oriented muscle force output, contributing to an overall improvement in the F-V profile. [4,5] In field sports, there is a greater emphasis on the ability to produce force horizontally in order to increase sprint acceleration towards peak velocity over shorter distances (0-30m), rather than developing the ability to maintain peak velocity over longer distances.[6] Therefore, training methods that are sport-specific, progressive, and require high strength demands are ideal for developing sprint acceleration within field sports. [7]

Current research identifies F-V adaptations are dependent on sled tow load. Heavy (>30% body mass [BM]) sled tow loads improve sprint acceleration through increases in F0 (horizontal), Pmax, and technical application of horizontal force. [3,4,7,9] However, it is also argued that the benefits of heavy sled loads may be undermined by acute changes to unresisted sprint kinematics over longer distances (>30m).[3.4.9] Light sled tow loads have conflicting results with some sources finding improvements in sprint performance through increases in V0 and Pmax >30m[10], while others have found no significant difference between light resisted and unresisted sprints.[7,9,10] When it comes to optimal loading to improve sprint acceleration, the general consensus is that heavy loads are better than light loads[7,9], however, the optimal load is still heavily debated partially due to the variability in loading methods such as %BM, velocity decrement (Vdec), and absolute loads, and if athlete variations and surface frictions are taken into account.[7,9] These discrepancies in the literature are thought to also be partially due to the differences in loading prescription methodology as well as the different equipment being used to both overload the athletes and to record the variables being investigated; including timing lights, radar systems, and force plates. [7,9,11] To date, the consistency of methodological standards used across sled tow studies has yet to be reviewed. Therefore, the purpose of this review is to compare the methodologies utilised in current sled tow literature, primarily focussing on the technologies utilised and the variables assessed in the context of field/court sport athletes.

2. Literature Search Strategy

To undergo the review, the following databases were used to source literature, SPORTDiscus, Science Direct, Web of Science, Google Scholar, and Pub-Med. Keywords used to search were as follows: sled tow, load-velocity, resisted sprint, sled pull, instrumented sled, sprint, resisted sprint, horizontal force, horizontal force production, sled load, and sled towing. The reference section of articles was also scanned to identify relevant literature.

2.1 Inclusion Criteria & Selection

The generalised selection criteria for consideration of inclusion in the review were as follows: (1) articles must have been published in a peer-reviewed scientific journal; (2) subjects must be participating in field and/or court sports from a recreational level and above; (3) articles were to be written in English and/or have an English translated version. Specific selection criteria for inclusion in this review required studies to have a strong focus on expanding current sled tow literature and therefore, (4) articles must have utilised a sled and the necessary sled towing equipment; (5) articles used needed to be either acute or longitudinal sled tow studies; (6) articles used needed to specify sled tow loads; (7) articles needed to include and report on the kinetic and/or kinematic sprint variables measured; (8) articles must include the measurement technologies utilised in the article. Articles that utilised sprinters only or a combination of sprinters and other athletes (not separated) were excluded. Conference presentations, book chapters, and summaries were excluded. Articles that did not meet the above criteria were automatically excluded from the review.

3. Study Characteristics

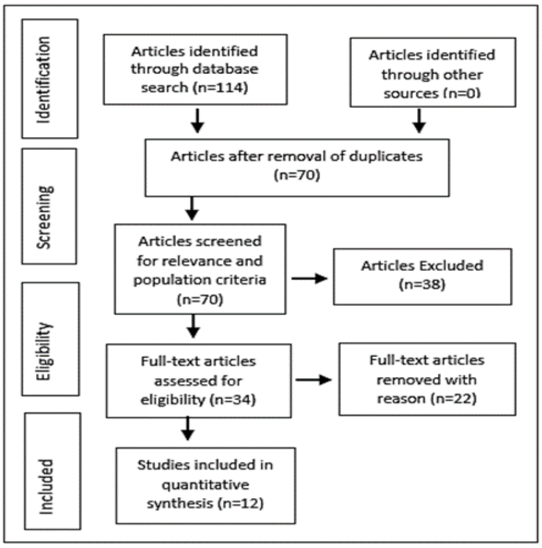

Figure 2. Diagram of study selection for review.

3.1 Article Characteristics

A total of 114 articles were identified after database searches, 70 articles remained after the removal of duplicate articles (Figure 2). Further removal of articles that did not meet population criteria, selection criteria, and those that had no English translation, 12 articles remained for inclusion in the review (Table 1). A variety of methods have been utilised to assess 5-45m sled resisted sprint variables including timing lights and radar device. Sled load prescription varied across articles with the most common methods used being %BM and %Vdec. Common variables reported included Pmax, maximal velocity (Vmax), ground reaction forces (GRF), F0, V0, and Vdec.

3.2 Subject Characteristics.

A sex bias can be identified within the articles included (Table 1.) with eight of the articles reviewed using only male subjects for testing[11,15,16,17,31,32,38,39], two articles used both male and female subjects[18,34], one article used only female subjects[37], while one article did not clarify the sex of subjects used[12]. The age of male subjects varies from 15.1 to 31.9 years of age. The male youth subjects tested in one article had a reported peak height velocity of 1.80 ± 0.80 years.[15] Female subjects' ages fell between 18.5 and 27.1 ± 2.30 years of age, however, due to age averages being combined with males, a maximum age could not be determined. 10 of the 12 articles reported the mean weight of subjects. The weight of male subjects ranged between 64.2 kg to 114.4 kg. Only one article reported female weight on its own being 64.8 ± 8.70 kg. All 12 articles reported mean height of subjects, however, the two articles that used both male and female subjects used combined mean height rather than male mean height and female mean height.[18,34] Male height across all studies varied from 1.76 ± 0.36 to 1.83 ± 0.72m. The female-only article reported female height as 1.68 ± 0.65m.[37] The field sports that subjects participated in varied with eight articles reporting participation in rugby union[11,15,16,18,31,32,38,39] and five articles reporting participation in soccer.[11,17,18,31,37] The skill level of the subjects that participated varied across the literature. Three studies used recreational/amateur level athletes[12,15,17], four studies used regional/semi-elite level athletes[16,31,34,38], three studies used national/elite level athletes[18,32,39], and a further two studies used a mixed level range of athletes[11,37].

4. Measurement Systems

4.1 Radar Technology

Five of the studies utilised a radar device to measure sprint performance during sled tow sprints.[12,15,16,17,18] The same radar device (Model: Stalker ATS II, Applied Concepts, Dallas, TX, USA) was utilised to assess sled tow variables at sampling frequencies of 46.9-47Hz, providing methodological consistency across the literature. [12, 15, 16, 17, 18] Radar technologies are often used to assess on-field linear sprinting with immediate sprint performance measures such as displacement, acceleration, V0, maximal theoretical power (P0), and F0, making them an easy measurement device to use during sled tow sprints.[19,20] These measures provide necessary information to formulate a force-power-velocity (F-P-V) profile for individual athletes.[19] Only one study reviewed stated that the radar technology was reliable and valid, however, no specific statistical values were reported.[12] The radar variables most commonly reported were Vmax, Vdec, and V0.[12,15,16,17,18] Radar devices are placed directly behind the athlete (1-20m) and typically placed on a tripod at 1m height and/or in line with the centre of mass (COM).[19,20] Radar devices work off a doppler principle and therefore are best utilised for linear accelerations/decelerations.[19] A review on the reliability measurements of sprint performance across 2-100m using radar technology has been reported on from across literature.1 [19] In field-based and team-sport athletes, the validity of radar devices across 34 studies was generally considered acceptable amongst all populations (R^2= 0.87-0.99, absolute bias of 3-7%) when compared to force plates and photoelectric cells.[19] Radar technologies are shown to have acceptable intra-day reliability (CV ≤ 9.5%, bias/systematic error ≤ 4.1%, ICC ≥ 0.84) and a minimum of moderate inter-day reliability (bias/systematic error ≤6%, ICC ≥ 0.72) for distances up to 100m.[19,20,21,22] More specifically, intra-day and inter-day reliability of sprint performance over the 20-30 m split has been determined as acceptable for V0, F0, Pmax, slope, and relative slope (ICC ≥ 0.75, & CV ≤ 10%), while 2-10m split times are considered moderately reliable for relative F0, and relative Pmax.[20] This is thought to be due to the introduction of and increases of angle error (15^{o} angle error = 3.4% recorded speed error). [19, 20] Radar technology limitations exist across short distances of 0-5m, particularly from a standing start.[19] This is thought to be due to postural changes, and therefore, restricting valid and reliable information surrounding first step quickness when utilising radar technologies.[19,20] Radar technology is a beneficial and favourable technology for many coaches due to its transportability, easy field use, high reliability, and ability to provide instantaneous feedback during sled tow sprint efforts.[19,20] However, coaches should be cautious when interpreting data from the first few steps due to potential increases in error.

4.2 Laser/Timing Light Technology

Five studies have utilised a single or dual-beam timing light system (Microgate, Bolzano, Italy: Swift Performance Equipment, Lismore, Australia: Fusion Sport, Queensland, Australia: Brower Timing System, Utah, USA).[11,16,31,37,39] Of these studies, one[37] reported reliability for single beam (ICC=0.87-0.96, CV= 1.2%[0-20m] and 1.4% [20-40m].[29,37] The most common variables measured were Vmax, Vdec, and sprint time. [11,16,31,37,39] Timing lights are considered to be 'gold standard' for sprint timing, acceleration, and speed assessment, with accuracies/samples of up to 1/100 of a second (3/100 for 2-10m), therefore, it is seen amongst the literature to be an appropriate assessment tool for sled tow research. [11,24,25] Most timing light systems use photocell technology that emits an infrared beam to a reflector (approximately 2m away) which bounces back creating what is known as a 'gate'. When the gate is broken by a body, a recording is taken by a timing chip.[24, 25] Timing systems can use single, dual, or triple photocells; the more photocells are present, the less likely error and bias are to be introduced, and the higher the cost of the equipment.[24] Timing lights are most commonly used to measure sprint speed (m/s), Vmax, and sprint speed at various stages (split phase). Using these measures and the body's COM displacement-time curve over sprint acceleration. Samozino, et al.[23], formulated an equation to be able to derive valid and accurate F-P-V profiles from timing lights when compared to force plates (very low bias, <5%). Single beam timing lights are commonly used for sprint testing due to their affordability, availability, and increased accuracy in comparison to stopwatches.[25,29] However, research has shown that single-beam timing lights can introduce significant error due to false signals often being triggered early by the leading limbs (e.g. outstretched arm and/or leg) instead of the torso/hip area, and therefore, the use of single-beam timing lights for sprints <20m is widely criticised due to its reduced accuracy and validity.[26, 27, 28, 29] In regards to set up height, different heights have shown to affect the measurement accuracy, with optimal height for single-beams determined as 0.91m (36 inch) or 'hip height', however, athlete height differences can still introduce error.[27, 28] In dual-beam systems, differences were also found between set up heights with CV differences between 0.69-1.2% (60 and 80cm) with greater variability identified at shorter distances (0-10m).[24] When assessing time differences between single-beam and dual-beamed timing lights, time differences have been reported as minimal when arm and leg movement interference is eliminated (cycle sprints), therefore confirming limb motion and timing light height being the most common causes of error for timing light systems.[29] When single-beam is directly compared to dual-beam timing systems, research has found absolute time differences that ranged from -0.05 to 0.06 seconds across a 20m sprint, most likely caused by a swinging arm or forward body lean setting off the single-beam system early.[29] However, it should be noted that dual-beam systems are not always available primarily due to the higher cost of the equipment.[25] It has been reported in timing systems that as distances increase, relative error decreases, and therefore suggests, that timing systems have limited reliability for measuring first-step quickness (0-2m) and early acceleration (<10m).[20, 24,29] Overall, timing light systems can provide a practical on-field means for strength and conditioning coaches to assess velocity and time-based variables during sled tow sprints.[25,26,27] However, the literature suggests that single-beam timing systems are not recommended for strength and conditioning coaches wanting highly accurate and reliable sprint times or in research/scientific settings.[27,28, 29]

4.3 Force Plates

Two studies utilised force plates to assess sprint performance using sled tow, however, neither study reported reliability or validity.[,31,34] Force plates have been commonly used for many years to assess sprint kinematics and kinetics such as forces and moments in all three directions (x,y,z axis).[54,55] Kawamori, et al.[31], utilised three force plates (2.7m connected length) and an extended tether (23.1m length) to measure GRF's at a sample rate of 1000Hz (Type 9287BA, Kistler Instrument Corp., Winterthur, Switzerland, 0.9 m long, equipped with piezoelectric sensors [KI 9067; Kistler, Winterthur, Switzerland]).[31] The requirement of a 23.1m extended sled tow tether (original tether = 3.90m) was needed in order to prevent the sled from being dragged over the plates, this, in turn, alters the angle of pull, and potentially affects the GRF results, (i.e. greater horizontal GRF and decreased vertical GRF).[31]

The use of force plates in sled tow research is scarce likely due to a number of limiting factors. Cost is a factor often limiting the number of plates available for testing, resulting in only one step occurring on the force plates; therefore, only one step to assess GRF data which result in findings unable to represent anything over approximately 0.90m and the inability to represent an overall GRF pattern over an acceleration phase.[61] When a limited number of force plates are used in assessment, error can be introduced through participants 'targeting' the force plates, resulting in changes to peak impact forces and their timings due to the changes in gait.[45,49,61] To date, literature utilising force plates to measure unresisted sprint performance have typically used a series of connected time synchronised force plates to cover at least 6.6m (some studies in sprint athletes have recently utilised up to 50m) in length in order to measure 3-5 foot contacts, and at a sample Hz ≥500.[45,46,47] However, since force plate use in sled tow research is limited by the inability to directly drag a sled over the plates as this risks damaging the plates and leading to error, the use of multiple force plates may be problematic.[31] Furthermore, most force-plate research is conducted in a laboratory setting different from that field or court sport athletes may experience when performing sled tow sprint training.[55]

In an effort to more accurately measure sprint performance in the field, advances in force plate technology have resulted in the development of portable force plates.[55] The purpose of portable force plates is to allow accurate testing within the field and enables testing to be more sport/sprint specific versus using a non-motorised treadmill.[55] The ability to use portable force plates in the field has allowed for instant measures of unresisted sprint-phase kinetics in a timely manner, which can then be used to understand the utility of resisted sprint towing from a foot-ground contact perspective.[55] To expand on force plate usability, a study investigated the validity of using portable force plates to measure sprint starts, horizontal jump and vertical jump found that all variables assessed across the tasks were highly correlated with standard force plates ($p = <0.001$; the mean CV of the relative bias were very low (0.3 to 1.3%) for vertical and horizontal peak forces, vertical and horizontal impulses, time to vertical and horizontal peak forces suggesting good repeatability for each task; bias ranges and root mean square error (RMS) ranges for each variable were, vertical peak force- 0.8 ± 0.6%, RMS error 1.5 ± 1.4%, horizontal peak force- −10.8 ± 2.7 to −18.7 ± 9.0%, RMS error 10.8 ± 2.7 to 18.7 ± 9.0%, vertical impulse- 0.8 ± 0.8 to 1.2 ± 0.8%, RMS error 1.0 ± 0.4 to 1.3 ± 0.7%, horizontal impulse- −9.6 ± 2.5 to −11.0 ± 2.8%, RMS error 9.6 ± 2.5 to 11.0 ± 2.8%.[48] However, this technology is still limited by its ability to only measure sprint start toe-off due to the force plate being elevated above ground requiring the athlete to set up a sprint start with the back foot on the portable force plate with a kick plate attached and the front foot on the track.[48] From the GRF data available from force plate assessments during unresisted sprinting, many coaches and researchers are able to determine the foot contact time by the time that vertical GRF rose above 10N (foot strike) and reduced below 10N (toe-off).[31] Braking and propulsive phases can also be determined by the positive and negative horizontal GRF.[31] This instantaneous information provided by force plates is useful to coaches as it can be used to determine power output consistency/imbalances and manage changes to F-P-V output as a result of training.[55] Due to the number of force plates needed to accurately measure step to step sprint performance and avoid error introduced by changes in running gait from force plate targeting, many coaches opt for different measurement technologies such as radar and timing lights due to the high costs and expertise involved in using force plates; although it is noted that these technologies do not provide a comprehensive overview of step kinematics and kinetics.[45,46] Furthermore, force plate use in sled tow research is also limited by the inability to directly drag a sled over the plates as this risks damaging the plates.[31] Therefore, caution should be exercised when interpreting results when using a limited number of force plates as there may be increased error in results due to athletes targeting the force plates.

4.4 Global Positioning Systems (GPS)

From the literature reviewed, one study utilised GPS technology to assess sled tow sprinting.[32] No reliability or validity statistical values were reported. GPS systems are an increasingly popular tool used amongst team sports for measuring sprint kinematics such as Vmax, as well as measuring other useful data such as total distance.[50,56] GPS is able to measure the distance travelled by an athlete using their positional differentiation from changes in device location using satellite signals.[56] GPS devices have many benefits including, allowing assessment out on sporting fields, monitoring athlete load via total distance, allowing real-time feedback to coaches, and enabling for data collection of multiple participants at once [30,50,51] Tierney, et al., utilised GPS micro-sensor technology units (StatSports Group Limited, Co.Down, Northern Ireland), collecting 10Hz GPS data (augmented to 18Hz), accelerometer data at 600Hz, magnetometer data at 10Hz, and gyroscope data at 400Hz in their study of using momentum as a load prescription method similar to %Vdec to assess Vmax over a resisted 40m sprint.[32] Research has shown that the assessment of Vmax from a 40m sprint is considered valid using GPS at 10Hz when compared to a 50Hz radar gun with a mean bias of <0.19 being trivial (<0.19=trivial, 0.2-0.59=small, 0.6-1.19=medium, 1.2-1.99=big).[51] However, there is also research during unresisted sprinting contradicting this, with typical error ranging from 3-15% and ICC ranging from 0.93-0.96, suggesting that GPS may not have acceptable validity as differences as small as 2% in sprint velocity error are equal to the difference between the 50th and 70th percentile (small effect magnitude) in team sport male athletes for a 20-m unresisted sprint.[30,52,53] The validity and reliability of GPS technologies are primarily affected by sprint velocity, sample rate, sprint distance, and movement patterns, i.e the higher sprint velocity is or the lower the sample rate is, the lower the validity and reliability will be, suggesting that sled tow sprints may have higher GPS validity/reliability due to the reduction in sprint velocity.[30,53] Therefore, more research needs to be undertaken to determine the validity and reliability of GPS during sled tow sprints, particularly as future developments occur with GPS technologies.[30] In regards to limitations, it should be noted that GPS is limited to outdoor use only as it requires a direct signal to a satellite. Therefore, coaches should take into consideration the Hz used and the environment (outdoors) where they plan to undergo testing using GPS devices.

5. Methodologies

5.1 Evaluation Protocols

Regarding testing standardisation, and the testing protocols in the reviewed literature, the information reported and observed varied amongst the research with nine articles clearly defining a standardised warm-up prior to testing[11,12,15,16,17,18,31,37,38], seven articles clarified if familiarisation sprints were undertaken and/or if participants were already familiarised with sled tow testing[12,15,31,34,37,38,39], seven of the articles defined the weight of the sled used [12,15,16,31,32,37], 11 articles defined the rest periods prior to testing and between sprints[11,12,15,16,17,18,31,34,37,38,39], and all articles ran a baseline unresisted sprint followed by multiple trials.[11,12,15,16,17,18,31,32,34,37,38,39] These reported measures all play a role in strengthening the methodological procedures of the current research presented. Researchers undertaking sled tow research have utilised distances ranging from 5-45m, with the most common resisted sprint distance used across the literature being 20m. Most studies utilised a 3-point start position which is considered to be the most common sprint start position for team sport testing.[30] This is important to report particularly in the studies utilising timing lights as starting positions are known to introduce error and have the potential to cause mistrials from early light triggers associated with reaction times, COM placement, and momentum.[30,57] It was common across the literature reviewed for researchers to undertake standardisation protocols to minimise the influence of internal and external factors on results. These protocols included familiarisation sessions, limiting or excluding high-intensity exercise for 24 hours prior to testing, wearing 'normal' training gear including clothing and training shoes/boots dependant on testing surface, and timing rest periods post-warm-up and pre-testing.[11,12,15,16,17,18,31,32,34,37,38,39] The longitudinal sled tow studies utilised the same training session approach of 2x training sessions per week.[17,18,32,39] Most of the articles reviewed reported the type of harness used to attach the sled being either a shoulder harness [12,18,31,37,38] or waist harness[11,15,16,17,34], as well as the length of the tether which most commonly varied from 3.00-5.00m[11,1215,16,18,37], with the shortest at 1.60m[38] and the longest at 23.1m[31]. Harness attachment is known to affect sled tow kinetics such as increased horizontal impulses when attached at the waist versus the shoulders (increase of 22.5% vs 17.5%). [7,33] This is thought to be due to the differing frictions of the sled, differences in forward lean/angle of tether, as well as starting position differences in COM [7,33] When the harness is attached at the shoulders, there is a greater influence on knee and trunk joint kinematics compared to the waist attachment ($p = <0.05$).[33] This has led to the suggestion that during sled tow, harnesses should be attached at the waist, where possible, due to the reduced alterations to sprint kinematics and increased net horizontal impulse.[33] However, this study only utilised loads of <10% Vdec

Table 1. Results of Acute and Longitudinal Studies Evaluating Sled Tow Load-Velocity (** Longitudinal Studies)

STUDY	Subjects	Measurement Technology	Evaluation Protocol	Load	Variables	Results
COCHRANE ET AL. [38]	N=12, Male Age: 20.4 ± 1.2 Height: 1.83 ± 0.72 cm Rugby Union	Custom-manufactured velocimeter (PowerLab4/25T, AD Instruments, Dunedin, NZ). EMG	2x 20m baseline un-resisted sprints, 2x 20m resisted sprints, 20m un-resisted sprints at 2, 4, 6, 8, 12, and 16 minutes of recovery. Velocity taken at 5, 10, 15, and 20 m	Initial load of 75% and 115% BM, 35% and 55% velocity decrement (VD)	Maximum Velocity (ms-1) PAP	Sled loads reducing maximal velocity by 35%, improved velocity at 20m (p=0.05, ES = 0.21) compared with 55%, no significant change at 5, 10, or 15m. A significant decline in velocity occurred at 12 (p= 0.01, ES = 20.61) and 16 min (p , 0.01, ES = 20.45) compared with baseline velocity (PAP lost after 12 min recovery).
CAHILL ET AL. [15]	N=70, Male Age: 16.7 ± 0.9 Height: 1.77 ± 0.69cm Weight: 75.6 ± 10.9 kg Rugby Union Lacrosse	Radar device (Model: Stalker ATS II, Applied Concepts, Dallas, TX, USA)	1 x un-resisted baseline 20m sprint 3x resisted 20m sprint	Vdec of 10, 25, 50, and 75%	Maximum Velocity Velocity Decrement	L-V relationship were reliable (coefficient of variation (CV) = 3.1%). L-V relationship were highly linear (r > 0.95). High between-subject variability (95% confidence intervals) in given Vdec loading, e.g loads of 14–21%BM causing 10% Vdec, 36–53%BM causing 25% Vdec, 71–107%BM causing 50% Vdec, and 107–160%BM causing 75% Vdec.
****TIERNEY ET AL. [32]**	N=13, Male Age:25 ± 3 Height: 1.86 ± 0.06m Weight: 103.9 ± 10.7 kg Rugby Union	Micro-sensor technology units (StatSports Group Limited, Co. Down, Northern Ireland). 10Hz GPS data (augmented to 18Hz), accelerometer data at a rate of 600Hz, magnetometer data at a rate of 10Hz, and gyroscope data at a rate of 400Hz.	8 weeks training phase of resisted sled sprint training sessions. Data collected as part of the subjects usual athletic performance training	Baseline- 10 m resisted sprint at a total external resistance of 30 kg, 45 kg, 60 kg, 75 kg (sled and harness mass = 14.8 kg)	Resisted Sled Momentum, BM Momentum, Vmax	Calculation of momentum is an easily applicable and practical method of determining an optimal load during RSS training for improving acceleration and sprint performance.
ZABALOY ET AL. [16]	N=20, Male Age: 22.5 ± 5.3 years Height: 1.80 ± 0.05 m Weight: 80.2 ± 15.2 kg Rugby Union	Timing Gates- Photoelectric cells (Microgate, Bolzano, Italy) placed at 1 m height on the start line and at 5, 10, 20, 25, and 30 m. Radar gun (Stalker ATS II, Applied Concepts, Richardson, TX, USA), sampling frequency of 47Hz an placed 5 m behind the starting line at 1 m height. Linear position transducer (Chronojump, Boscosystem, Barcelona, Spain). Force Plate (Kistler 9286BA, Winterthur, Switzerland) sampling at 350Hz.	Day 1: 2x 30 m sprints at each different load. Day 2 (72hrs later): CMJ, SJ, and dynamic (i.e., 1RM Squat) and isometric (i.e., squat and SIST) assessments were conducted.	30M Sprints= 0%, 20%, 40%, 60%, and 80% BM, randomly applied. 1RM Strength	Vmax Vdec Max Jump Height Relative Peak Power Resultant Mean Force Mean Propulsive Velocity	Moderate to strong correlations were found between Vmax, SJ, and CMJ (height), although Vmax was not associated to SIST or SISTrel.

KAWAMORI ET AL. [31]	N=10, Male Age: 27.9 ± 1.9 Height: 1.76 ± 0.06 m Weight: 80.2 ± 9.6 kg Mixed Team Sports (basketball, soccer, rugby, baseball, Australian rules football)	Electronic timing light system with double-beam photocells (Swift Performance Equipment, Lismore, Australia). Force plates at 1000Hz (Type 9287BA, Kistler Instrument Corp., Winterthur, Switzerland, 0.9 m long).	2x 5m sprints at each load with 1.5-2min rest between sprints.	0%, 10%, and 30% BM	GRF Contact time, Toe Off, Foot Strike Braking and Propulsive Force	Towing a sled weighing 30% of body mass increased relative net horizontal and propulsive impulse production compared to unresisted sprinting ($P < 0.05$).
CROSS ET AL. [12]	N=12, , (Sex not clarified) Age: 27 ± 4 years Height: 1.76 ± 0.08 m Weight: 82.5 ± 10.47 Mixed Sports (Field Sport n=11)	Radar device (Model: Stalker ATS II, Applied Concepts, Dallas, TX, USA) set on a tripod 5m behind the athlete at 1m height. Velocity–time data collected at a rate of 46.9Hz. Calibrated plates (Model: PL Comp Discs, Eleiko Sport, Halmstad, Sweden).	7x max velocity sprints. Distances set at 45 m for unresisted, 40 m at 20%, 30 m at 40%, 30 m at 60%, 30 m at 80%, 20 m at 100%, and 20 m at 120% BM.	Unresisted, 20%, 40%, 60%, 80%, 100%, and 120% BM	F0, L0, V0, Pmax, Pmax 2, SFv, Fopt, Lopt, and Vopt	Mechanical relationships can be accurately profiled using common sled-training equipment. F-V profiles and optimal loading conditions can be accurately and reliably profiled during multiple over-ground sprints.
PETRAKOS ET AL. [37]	N=17, Female Age: 20.5 ± 2.0 years Height: 1.68 ± 0.65 m Mixed field sports (field hockey, soccer, Gaelic football) Weight: 64.8 ± 8.7 kg	Infrared, single-beam speed gates (Fusion Sport, Queensland, Australia) were placed at 0, 10, and 20 m, at a height of 1 m.	Repeat resisted sprints until failure at load increments of 0.5-5kg	Initial load of 15%BM	1RM	Maximum resisted sled load was “moderately” and “strongly” correlated with ($p <0.05$) percentage fat free mass, countermovement jump, loaded countermovement jump, rate of force development, horizontal jump, and horizontal bound performance. MRSL is reliable for determining max acceleration load over 0-20 m.
COTTLE ET AL. [34]	N=17,n=10 Male, n= 7 Female Age: 20.9 ± 1.1 years Height: 1.7 ± 0.1 m Weight: 62.2 ± 22.1 kg Field & Court sports	AMTI BP400600 force plates (AMTI Watertown, MA, USA) set at 2400Hz. Visual 3D (C-motion, Germantown, MD, USA).	5x approx 10m sprint trials at each load	0%, 10%, and 20% BM	Ground reaction force, impulse, peak propulsive GRF, rate of force development (RFD)	Propulsive GRF & impulse were greater in 20% BM condition than unweighted in both limbs and 20% BM condition was greater than the 10% BM condition in the front leg only, and vertical GRF impulse was greater in the 20% BM than unweighted. 10% BM load was not sufficient to increase propulsive GRF impulse.

MURRAY ET AL. [11]	N=33, Male Age: 21.1 ± 1.8 years Height: 1.82 ± 0.1 m Weight: 83.6 ± 13.1 kg Rugby Union & Soccer	Timing gates (Brower Timing System, Utah, USA). Video camera (Panasonic, NV-MS5 SVHS Video Camera) placed at a 90 degree angle to the 20 m gate	2 sets of 7x sprints across 20m	0, 5, 10, 15, 20, 25 and 30% BM.	Stride length Stride frequency Sprint time	Statistically significant (but not meaningful) quadratic relationship between sprint time and resistance as sprint time increased from 2.94 s to 3.80 s from 0 to 30%BM resistance. As resistance increased, stride length shortened, there was no change to stride frequency.
****MORIN ET AL. [17]**	N=16, Male (n-10 experimental, n=6 control) Age: experimental- 26.3 ± 4.0 years, control- 26.8 ± 4.2 years Height: experimental- 1.77 ± 0.08 m, control- 1.75 ± 0.08 m Weight: experimental- 74.5 ± 5.3 kg, control- 70.7 ± 6.5 kg. Soccer	Radar device (Stalker ATS Pro II, Applied Concepts, TX, USA).	16 sprint sessions over 8 weeks. 2 blocks of 5x 20m sprints.	Experimental- 80%BM Control- 0%BM	Velocity Horizontal GRF Horizontal power output Theoretical max velocity and force	Very heavy sled tow increased max horizontal-force production compared with unloaded sprint training (effect size of 0.80 vs 0.20 for controls, unclear between-groups difference) and mechanical effectiveness (ie, more horizontally applied force; effect size of 0.95 vs –0.11, moderate between-groups difference). 5-m and 20-m sprint performance improvements were moderate and small for the very-heavy sled group and small and trivial for the control group.
****WEST ET AL. [39]**	N=20, Male (Sled group, or traditional group) Age: SLED-26.8 ± 3.0, TRAD-25.1 ± 3.2 years Height: SLED-1.86 ± 0.80, TRAD- 1.85 ± 0.70 m Weight: SLED- 90.2 ± 10.3, TRAD- 90.9 ± 10.6 kg Rugby Union	Electronic timing gates (Brower TC-System; Brower Timing Systems, Draper, UT, USA), set up at the start line and then 10 and 30 m.	12 sessions over 6 weeks. SLED- 3x20m resisted sprint TRAD- 3x20m unresisted sprint (Pre and Post-test of 10 and 30m)	SLED- 12.6% BM TRAD- unresisted sprint	Velocity	Both training programmes improved participants' 10 and 30 m speed (p= <0.001), but pre to post-testing in 10 m (p= <0.001) and 30 m (p= <0.003) sprint times were significantly greater in the SLED training group. Similarly, the percent change within the SLED group for the 10 m (p= <0.003) and 30 m (p= <0.003) tests were greater than the TRAD group.

****CROSS ET AL. [18]**	N=15 (Soccer), Male, N=21 (Rugby Union), n=9 male, n=12 female Age: 27.1 ± 4.8 years (S) 27.1 ± 2.3 years (R) Height: 1.76 ± 0.36 m (S) 1.75 ± 0.97 m (R) Subjects divided into even groups within their sport, one as control, the other experimental. Rugby Union & Soccer	Soccer- Radar gun (Model: Stalker ATS II, Applied Concepts, Dallas, TX, USA), attached to a tripod set at 5 m and a height of 1 m, collecting outward bound velocity-time data at 46.9Hz. Rugby- 1080 Sprint, (2000 RPM OMRON G5 Series Motor, OMORON Corporation, Kyoto, Japan.), collecting velocity-time data at a rate of 333Hz.	12 sessions of 10 × 20m and pre/post-profiling, at 10% decrement in individual maximum velocity, or at individualised optimal loading for maximal power.	Pre/Post Testing: 0, 25, 50, 75 and 100% BM Distance based on maximal velocity (30-m at 0%, 30-m at 25%, 20-m at 50%; 20-m at 75%; 15-m at 100% BM or its´ 1080 Sprint equivalents).	Velocity Horizontal power Maximum theoretical velocity and force	Group effects of sprint training at optimal power did not appear to be substantially different than training using traditional lighter loading protocols. individual adaptations to the type of training imposed were varied, leading to a conclusion that pre-training F-v profile may have contributed to the results observed.

over 6m, a distance known to have high variability.[7,33] Therefore, more research is required in this area at different loads and distances to confirm the effects of harness attachment on sled tow sprint performance.

Surface type, or more specifically, coefficients of friction, have been identified across research as having an influence on sled tow sprint kinetics resulting in potential changes in stimulus for any given load, making it difficult to directly compare research and prescribe correct loading.[42, 43] Several articles identified the type of surface sled tow testing was carried out on and if it was indoors or outdoors, which is important to acknowledge as research has identified how different surface types (friction) can impact on sled tow results, and therefore not all sled tow research may be directly comparable.[42] A study investigating differences in coefficients of friction across different surfaces (synthetic athletics track, 3G football pitch, artificial grass hockey field, and grass rugby field) identified substantially different coefficient of friction values across the surfaces (μ= 0.21-0.58).[43] In a 30m sled tow sprint with 30%BM, the hockey field (lowest μ) had a significantly lower rate of sprint time increase than the other surfaces, while the other surfaces had no difference between them even though they had significantly different coefficients of friction.[43] This result conflicts with previous work by Andre, et al.[44], who found changes in coefficients of friction as load increased across all surfaces.[42,44] What is unclear is how determining the coefficient of friction of each surface may be influenced by factors such as changes in sprint kinematics on different surfaces, surface levelling, and the stiffness and energy dissipation properties of the surfaces, resulting in a more complex relationship between rate of sprint time increase and coefficients of friction.[37] Overall, the key areas of sled tow testing protocol research has identified as having increased influence on test outcomes and testing associated error include starting position, sled attachment point, and surface type, particularly for repeat testing and comparisons.[7,30,33,42,43,44,57] Therefore, practitioners and future researchers should take these areas into consideration and exercise caution when developing their evaluation protocols.

5.2 Loading Parameters

A multitude of loading methods have been utilised across research with sled loadings differing depending on which method was used. The research reviewed used loads varying from 0-120% BM[11,12,16,17,18,31,34,37,38,39], 10-75% Vdec[15,38], and 30-75kg absolute weight[32,37], with two studies utilising a mixed-methods approach to loading[37,38]. The most common method currently used for loading is %BM as it is relatively easy to prescribe loads across athletes due to the known linear relationship that as weight increases velocity will decrease and horizontal force increases.[7,15] However, when %BM and/or absolute loads are used uniformly across a group of athletes, the training intensity/stimulus will differ between athletes as it does not take into account differences in changing friction coefficients, strength and power capabilities, sprint technique, and F-V characteristics [7,15,31] In pursuit of a method that does take into account strength capabilities, Vdec has quickly become a popular method of assigning individualised sled tow loads based off of the percentage decrease in velocity rather than %BM. Vdec is thought to offer a more accurate individualised approach to sled loading while taking into account factors such as BM and strength.[7] Vdec is based on the same linear relationship as %BM with increasing load resulting in decreasing velocity and increasing force. When optimising loads for power development, research concluded optimal loading mostly ranges between 69-96%BM, dependent on the individual, whereas the optimal load range when using Vdec was narrower (48-52%), and therefore, could provide a better guide for targeted training stimulus.[7,12, 31] However, a recent systematic review on resisted sprint training for sprint performance[10] highlighted between-study differences in the methods used to prescribe load using Vdec, with some studies using average velocity over 0-10m to prescribe %Vdec while others used 0-20m and 0-50m average velocity.[10,37] The review[10] noted that this may decrease the external validity of the methodology when trying to compare studies as the %Vdec for 0-10m and 0-20m may not be equal to the %Vdec from a 0-50m sprint.[10,37] Therefore, the external validity of this loading method has been brought into question due to the inability to directly compare findings across the literature.[10,37]

Recently, research has branched into other possible methods of load prescription. Petrakos, et al.[37] recently explored the traditional 1-repetition max (1RM) load prescription method in order to take into account athletes' power-BM ratio.[37] Rather than using Vdec, an athlete would otherwise be prescribed a %1RM depending on the phase of the sprint, and thus strength capability, being targeted (i.e. speed-strength, power, strength-speed).[37] Maximal resisted sprint load test (MRSL) has been defined as the maximal sled tow load used before an athlete can no longer accelerate between two phases of a sprint (e.g. 10-15m & 15-20m).[37] Petrakos, et al.[37], study also sought to identify reliability, correlations for MRSL tests.[37] Moderate and large correlations were confirmed between MRSL and other performance metrics, such as rate of force development (RFD) (r=0.45), countermovement jump height (r=0.58), loaded countermovement jump (r=0.60), % fat-free mass (r=0.59), and horizontal jump (r=0.58), however, there were no very large or near-perfect correlations.[37] Based on these findings, it was proposed that the MRSL prescription method may take into account individual athlete characteristics such as speed, power, and body composition.[37] The MRSL method has been found to be reliable (ICC=0.95, CV= 7.6%) and two different equations to predict initial load have been established through multiple regression analysis, explaining up to 53.5% of the variance in MRSL.[37] To date, this method has only been tested up to 20m, however, future testing may determine if this test can be used over different distances to target different strength capabilities.[37] The ability for strength and conditioning coaches to utilise the prediction equations for initial load of MRSL are extremely limited by the necessary equipment required including force plates and a hexagonal bar, the level of the athletes, and surface type, and therefore, are better suited to either research settings or high-performance teams with access to such equipment.[37]

Another recently investigated method of loading includes the use of peak momentum to optimise acceleration performance. [32] This method is based on the principle that momentum targets the different variables that improve sprint acceleration while taking into account an athlete's BM, current inter-individual differences in sprint performance, and adversely to %BM and %Vdec can be compared across various distances.[32] This line of research is promising for strength and conditioning coaches as it may provide a practical method for individualised load prescription that is likely to provide a sufficient overload stimulus for sprint performance improvement. However, there is currently only one published study that has examined this method with a number of limitations identified such as, disregarding friction, testing only using a shoulder harness, and testing only at a distance of 0-10m.[32] Therefore, more research is needed to confirm this theory, quantify momentum at various distances, and determine reliability and validity.[32]

The ongoing discussions and exploration of alternative loading methods to determine which method is best suited for individualised testing and training suggest that further research is required in this area to establish a gold standard method. Currently, research supports the utilisation of any of these loading methods to improve sprinting performance when a sufficient overload is prescribed. However, the methods that best support individualised loading such as Vdec and MRSL should be prioritised by strength and conditioning coaches if they have the capabilities.

5.3 Variables Assessed

5.3.1 Kinematic & Kinetic Variables

A number of kinematic and kinetic variables have been examined when towing sleds. Common sprint kinematic and kinetic variables investigated include stride length, stride frequency, sprint time, ground contact time, and various GRF's such as braking and propulsive forces, horizontal and vertical forces, and impulse.[11,17,18,31,34] In regards to acute sprint kinematic changes, increases in sled towing load hold a linear relationship with decreases in both stride length, and sprint time.[11] This is in line with Kawamori, et al.[31], who found sled towing at 30%BM resulted in increases in ground contact time and decreases in stride length (P= <0.05%) when compared to sprinting unresisted and with 10%BM.[31,58] However, stride frequency historically has been reported to decline non-linearly [60], with Murray et al.[11] reporting no significant change in stride frequency as load increased, suggesting that changes in stride frequency may vary between athletes. Literature has long debated whether acute improvements in sprinting from using heavier sled tow loads are beneficial due to reports of acute decreases in stride length, which is considered to be non-ideal and non-specific for sprinting.[11] However, it should be noted that outside of the sport of sprinting, the overall improvements to sprint performance are prioritised over subtle kinematic changes that would otherwise be inappropriate for a sprint trained athlete, and therefore resisted sprinting appropriately overloads stride length and may be a means to improve this performance metric.[10,11]

Research into the long-term effects of sled tow training appears to be relatively limited. Alcaraz, et al.[59], investigated the kinematic adaptations of a four-week sled tow training programme at 7.5%Vdec. The study found that sled-tow training resulted in increased stride length during the acceleration phase of sprinting with no effect on any other kinematics.[59] However, there were no significant differences between the sled tow training and traditional sprint training groups, suggesting the sled tow load may not have been heavy enough to illicit overload benefits[59]. It was reported that there was a 7.4% decrease in the knee angle of the supporting limb as a direct result of a 15.7% significant increase in trunk angle inclination during early acceleration[59]. As a result of the changes in trunk angle and knee angle, the COM sits lower to the ground potentially resulting in greater generation of propulsive forces in a horizontal direction during the acceleration phase, and therefore, resulting in improved sprint performance.[10,59] A systematic review looking into resisted sled sprint testing for sprint performance improvement by Petrakos, et al.[10], has highlighted that there is a variance in methodology amongst the literature on how sled tow sprint kinematics are interpreted with some studies using stride kinematics over certain distances and others using single-step kinematics at a specific distance.[10] This suggests that any kinematic changes should be interpreted with caution as study conclusions may be specific to individual methodological approaches used and distances rather than populations.[10] Although there is research suggesting heavy sled towing is not deleterious for sprint technique, the ongoing concerns and conflict amongst research using heavy sled loads suggests that more research is required to decisively conclude the longitudinal kinematic adaptations to sled tow sprint training.

Given that kinematics are the outcome of underlying forces, it is also important to consider the effects of sled towing on kinetic variables. Sled tow research has looked to determine what acute effects sled towing and loading has on force production, GRF, and RFD. Research has found that there is greater propulsive GRF impulse generated using 20%BM in both front and back legs in comparison to unresisted sprints and 10%BM, as well as, greater vertical GRF impulse in 20%BM sprints compared to unresisted sprints.[34] Loads of 30%BM have also found to significantly increased net horizontal and propulsive impulses due to longer ground contact times and increased application of horizontal forces on the ground.[31,34] These findings suggest that sled tow loads of ≤10%BM had minimal effects on GRF.[31,34] Moreover, sled loads of ≤10%BM may preserve sprint kinematics.[31] Therefore, while relatively light sled loads may not alter sprint mechanics, greater loads may be required to stimulate the musculotendinous adaptations that transfer more effectively to early phases of sprint acceleration.[34,35,36] These acute results suggest that sled towing at loads above 20%BM is sufficient to overload sprint kinetics, primarily horizontal GRF's.[31,34] Chronically, this type of resisted sprint training at loads above 20%BM could lead to long-term adaptations to horizontal force production and mechanical effectiveness for 5-20m sprint performance.[17]

Longitudinally, research has found sled tow training when utilised alongside traditional sprint training, can improve acceleration, speed, peak horizontal and vertical impulses, peak force, and RFD when compared to traditional sprint training alone.[39] This is thought to be due to the sled overload providing a sufficient stimulus to increase propulsive force through improvements in stretch reflexes, increased nerve conduction velocity, and increased muscular output.[39] Longitudinal sled tow training is also thought to increase leg stiffness and eccentric strength during ground contact, primarily in the braking phase, resulting in an increase in stride rate and decreased ground contact time.[39] However, this too has been contradicted in research with suggestions that increased propulsive and horizontal impulses are due to increases in propulsive duration and longer contact times, rather than force magnitude.[7] It is evident that more research is required into the longitudinal kinematic and kinetic adaptations following sled tow training, as well as for future research to streamline the methodology from which kinematic and kinetic variables are interpreted from.

5.3.2 Profiling Variables

A well-known sled tow relationship acknowledged across literature is the linear load-velocity (L-V) relationship.[7] The L-V relationship is characterised by a decrease in velocity as the load increases (linearity- r >0.95).[15,18] The L-V relationship is expressed as a parabolic power relationship when towing a sled.[15] Cahill, et al.[15], confirmed the linear L-V relationship to be reliable (CV = 3.1%) at Vdec of 10, 25, 50, and 75%.[15] More specifically, the loads used to confirm reliability of the L-V relationship were 14–21% BM causing 10% Vdec, 36–53% BM causing 25% Vdec, 71–107% BM causing 50% Vdec, and 107–160% BM causing 75% Vdec (CV = <5%) .[15] Understanding the L-V relationship and how it is expressed during sled towing, has enabled coaches to prescribe appropriate loads for targeted training stimulus.[15] These targeted training zones are dependent on which phase of sprint performance is being targeted, i.e high loads and low velocities for improvements to acceleration phase, and low loads and high velocities for maximal velocity phase.

Coaches often use the F-P-V relationship in conjunction with sport specificity to determine which phase of sprinting (e.g. early acceleration) and therefore which load and athlete should be prescribed.[12] The F-P-V relationship presents the neuro-muscular system's highest capacity to produce maximal force in the absence of velocity (V0), and the maximal velocity produced in the absence of force (F0)[12,15,18] When the optimal capacities of force and velocity are combined, it is expressed as Pmax.[18] Often, these F-P-V relationships are profiled and used to identify if an athlete is force or velocity dominant using the F-V slope with more negative F-V slope values indicating more force dominance ($-F0.V0^{-1}$).[65] They are then used to advise load prescription dependant on which side needs improvement to enhance sprint or sport-specific performance.[17,38,65] Historically, F-P-V profiling has been done using cycle ergometry or instrumented treadmills, however, these methods have not always been practical or sport-specific.[46] Cross, et al.[12], investigated the ability for F-P-V relationships to be profiled from multiple sled tow sprints, and if loading could then be optimised to enhance power based on the profiles.[12] The results confirmed that the mechanical relationships from multiple sled tow sprints could accurately provide F-P-V profiles for athletes in line with those produced from cycling, treadmill sprinting, and single unresisted sprints.[12] However, multiple sled tow sprints are required, and therefore, are not necessarily time-efficient or practical.[12] Optimal loading for power production through multiple sled sprints was identified with optimal loading ranges sitting between 70-96%BM across a range of athletes.[12] Following a similar concept of identifying optimal load prescriptions, Tierney, et al.[32], sought to identify and utilise peak momentum to prescribe sled tow loads.[32] The research found that momentum does provide a sufficient overload stimulus for improving sprint performance, as well as identifying optimal peak momentum which varies amongst athletes between 35-76%BM.[32] In regards to using F-P-V profiles to target either force or velocity, research has examined the effects of different loads on force-velocity outcomes. Morin, et al.[17], looked into the use of very heavy sled loading on sprint performance, finding loads of 80%BM significantly increased horizontal force production and mechanical effectiveness at 5 and 20m.[17] This study was the first to assess sled tow loads above 43%BM with findings suggesting that heavy sled loadings are suited to improvements in force production and application (early acceleration phase).[17] In comparison, research into optimal sled loading using Vdec to acutely improve sprint performance found that a Vdec of 35% significantly improved velocity over 20m in comparison to 55%Vdec, suggesting that lighter loads better enhance velocity (maximal velocity phase). If targeting improvements to peak power, F-P-V profiling is beneficial in order to identify force or velocity dominance, and therefore, prescribe loading accordingly.[12,17,18,38]

6. Conclusion:

Resisted sled tow as a method of sport-specific resistance training quickly gained popularity within strength and conditioning due to the strong transfer of adaptations from training to performance. The purpose of this review was to compare the current sled tow methodologies, technologies, and variables utilised and assessed in literature in the context of field and court sport athletes. The literature brings to light ongoing expansions of research as to what loads are best used to optimise different aspects of sprint performance, which method is best to prescribe load, if there is a trade-off between kinetic and kinematic variables when using sled tow, and if certain measurement technologies are better than others for sled tow assessment. Although, this review has identified a number of limitations, and therefore, a need for more research within resisted sled tow literature to further support the many promising applications of sled towing. Overall, research suggests that when targeting improvements in early acceleration/force production, heavier sled loads should be utilised, and when targeting maximal velocity lighter sled loads should be utilised. The current technologies primarily used are able to accurately measure various F-V related sled tow variables from mid acceleration onwards (>10m). However, there is limited technology and methods available that can accurately provide insight into kinetics during the early acceleration phase (<5m) and easily provide direct measures of kinetics and kinematics beyond 5m. This provides a space for future development of technologies/methods to accurately compute and/or report sled tow variable changes for this stage of sprint performance. Accurate feedback of variables associated with first-step quickness/early acceleration would provide significant insight required for appropriate and targeted training to enhance sprint performance in field and court sport athletes.

Conflict of Interest

The authors declare that they have no conflict of interest relevant to this review.

Chapter 3:

Accuracy of an Instrumented Sled to Measure Force-Velocity and Power-Velocity Outputs of Male Rugby Union Players During Sled Towing

Prelude:

With an identified gap in the availability of sport-specific within field sprint assessment technology, this chapter introduces a newly created overground sprint assessment tool being the instrumented sled. To date, there is no current research using the instrumented sled, therefore, this chapter has a focus on determining the accuracy of this new piece of technology. This is done by looking at the goodness of fit of the F-V and P-V relationships produced from the force, velocity, and power outputs of the instrumented sled in the semi-elite male rugby population. The necessary step of determining the accuracy of the instrumented sled enables its subsequent use in chapter 4, which looks to evaluate the discriminative ability of the instrumented sled by comparing F-V profiles and optimal loads between forwards and backs in the semi-elite male rugby population.

Abstract:

The aim of this study was to determine the accuracy of an instrumented sled to measure force-velocity (F-V) and power-velocity (P-V) outputs during overground sprinting. Seventeen healthy male semi-professional rugby union players performed maximal-effort sprints with the instrumented sled. The instrumented sled recorded kinetic and kinematic data from the sprint via a load cell. The F-V relationship was fitted with a linear regression and the P-V relationship was fitted with a 2nd order polynomial quadratic regression to determine the goodness of fit (i.e., accuracy). The F-V relationship was considered to be near perfect with a correlation coefficient of R^2= 0.983. Similarly, the P-V relationship was also found to also be near perfect with a correlation coefficient of R^2= 0.986. This study confirms the accuracy of the instrumented sled to measure F-V and P-V outputs during overground sprinting. This is of interest to coaches and future researchers as it provides an additional accurate measurement tool to assess sprint biomechanics in the field.

Introduction:

Sprint performance has often been assessed using sports science technologies such as sprint treadmill ergometers, timing lights, radar guns, mobile apps, force plates, and global positioning systems (GPS), or some combination thereof.[30,46,50,65,73] However, often these tools are inaccessible or too expensive for many athletes and coaches to practically implement.

Therefore, there is a need for updated technology that is accessible and can be used within the field.[46]

Common sprint performance measures of interest include horizontal force, velocity, power, and their mechanical relationships since these underpin an athlete's sprinting ability in conjunction with technical and physical capabilities.[65] The linear force-velocity (F-V) and parabolic power-velocity (P-V) relationships describe the athlete's mechanical capability to produce maximal theoretical force (F0), maximal theoretical velocity (V0), and maximal power output (Pmax).[10,20,62] F0 and V0 represent the intercepts of the F-V linear relationship while Pmax is the peak of the P-V parabolic relationship.[20,62] Two athletes can have near-identical Pmax measurements but the expression of their F-V relationship can be different as a result of either force or velocity dominance.[46,65] Because of the difference in individual F-V relationships, the ability for coaches to have access to on-field technology to measure sprint performance and use this information to profile athletes to optimise programming and training is of high importance.

An athlete's ability to produce high magnitudes of force alongside the ability to orient this force horizontally is directly related to sprint acceleration, resulting in a collective effort amongst researchers to develop methods and technologies to improve the assessment of sprint capabilities in a sport-specific field-based manner.[6,10,12,39,46] As a result of the demand for improved accessible measurement technology, and an increased focus on resisted sprint training for sprint performance enhancement, technological advances in the equipment used to measure sprint performance has led to the creation of a wireless instrumented sled.[42] The use of an instrumented sled enables coaches to assess F-V and P-V relationships during maximal resisted sprints across a range of loads in the field.[42]

With the introduction of an instrumented sled as new technology to assess F-V and P-V relationships in the field, the accuracy of this technology needs to be established. Therefore, the purpose of this study is to determine the goodness of fit for the F-V linear and P-V parabolic relationships when using an instrumented sled. Previous research by Cross, et al.[12] determined the measurement of F-V and P-V relationships during multiple resisted-overground sprinted with a Radar gun is accurate, however, to our knowledge, this is the first study to determine the accuracy of F-V and P-V measurements with an instrumented sled during resisted sprinting. It is hypothesised that both F-V and P-V relationships produced from the instrumented sled during overground resisted sprinting will be highly accurate (R^2= >0.9).

Methods:

Participants:

Seventeen semi-elite level male rugby union athletes (Age: 18.7 ± 0.7, Weight: 100.6 ± 15.6kg, Height: 181.5 ± 7.5cm) volunteered to participate in this study. Ethical approval was gained from Auckland University of Technology Ethics Committee (20/345). All subjects provided written informed consent and were aware of all necessary procedures, benefits and risks associated with the study. Subjects were required to have been selected to represent at regional level, have a minimum of two years rugby training experience, and have played at academy level or above. It was required that all subjects be in good health with no known performance restricting illness, disease, or chronic and acute injuries. Subjects were required to be injury-free (>3months prior to testing). All players were required to be 18 years or older to meet the requirements for testing. Subjects all had prior experience with some form of resisted sprint training and were currently in pre-season training.

Design and Procedures:

Testing procedures were completed in a controlled environment indoors on a synthetic turfed track. The subjects were instructed to wear their usual training gear including rugby boots. Subjects were split into groups of 3-6 to allow for adequate but not excessive rest time of approximately five minutes active rest between each maximal sprint and to appropriately follow Covid-19 restrictions. Prior to testing, subjects completed a ~13-minute warm-up which consisted of five minutes of foam rolling and band stretches, three minutes of jog specific dynamic exercises/stretches, and five sprint specific drills including 20m accelerations at 75, 80, 85-90, 95, and 100% sprint pace. No specific familiarisation session was undertaken due to the subjects already being familiar with various forms of resisted sprinting.

Testing consisted of all subjects completing four resisted sprint trials using a heavy-duty instrumented sled attached at the waist via a 5m nylon tether. Each trial was at progressive non-randomised loads of either 20, 40, 60, 80kg (backs, n= 6), or 40, 60, 80, 100kg (forwards, n= 11) dependant on position/weight. This allowed for the subject's BM to be taken into consideration and to test at light through to very heavy loads without exceeding 110%BM (Backs= <109.5%BM, Forwards= <108.6%BM). Subjects were set up with their feet behind a line in a three-point stance with tension on the tether and were advised when they could begin the sprint in their own time. Subjects were advised to sprint as hard and as fast as possible for the duration of the test to ensure maximal efforts were given for each trial. This resulted in no set distance given with a range of sprint distances for all loads and all individuals averaging between 10-20m with sprint distance typically decreasing as loads increased.

Equipment and Data Analysis:

Sprint assessment was performed using a custom-built instrumented sled which measures force and speed. The instrumented sled used was constructed out of folded steel framing and flat railings that lay flush with the ground surface (5.64kg: GetStrength, Model: HT 50mm Sled, Auckland, NZ). Attached to the front of the sled is a load cell that measures pulling forces between the subject and the sled (Model: 250kg S-Beam load cell, Millennium Mechatronics, Auckland, NZ: Model). An accelerometer was also attached to the sled to measure the acceleration (3-Axis Digital Accelerometer, Analog Devices, Massachusetts, USA). The sled was loaded with a varying number of 20kg calibrated Olympic-style lifting plates (Model: PL Comp Discs, Eleiko Sport, Halmstad, SWE).

Figure 3. Instrumented sled with load cell attached.

The data from the sled was wirelessly transmitted to a laptop at a sample rate of 1000Hz during each trial. Force and accelerometer data were processed using a fourth-order low pass Butterworth filter with a cut-off frequency of 15Hz and 5Hz, respectively (selected via residual analysis).[67] Accelerometer data was integrated to calculate velocity-time data. Maximum horizontal power (Pmax) was determined by the peak of the P-V relationship and modelled to fit the inverse exponential function of the velocity-time relationship using the previously validated least squares method.[12,66] Analyses were performed using MATLAB R2021a (MathWorks, Massachusetts, USA). The F-V and P-V relationships were assessed using biomechanical data (peak horizontal force [HFpeak], mean horizontal power [Pmean], and maximum velocity [Vmax]) produced from the resisted sprint trials averaged over 10 steps during the Vmax phase. Maximum theoretical horizontal force (F0) and maximum theoretical horizontal velocity (V0) were both calculated from the F-V relationship of each sprint trial.

Statistical Analyses:

The statistical analyses was undertaken using Microsoft Excel (Microsoft, Redmond, USA). Using the 10-step averages, F-V measures were fitted with linear regressions to describe the F-V relationship with goodness of fit reported as R^2 (Figure 3.) The P-V measures were fitted with a polynomial quadratic regression (second-order) to describe the parabolic P-V relationship with goodness of fit reported as R^2 (Figure 4.). The R coefficients were interpreted by the definitions of 0.0-0.9 (trivial), 0.1-2.9 (small), 0.3-0.49 (moderate), 0.5-0.69 (large), 0.7-0.89 (very large), 0.9-0.99 (near perfect), 1.00 (perfect).

Results:

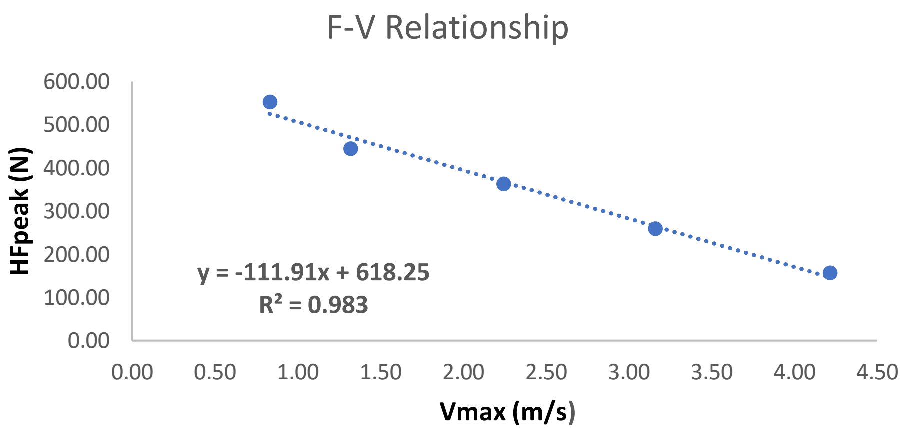

Figure 4. F-V relationship at increasing loads during multiple resisted sled sprints.

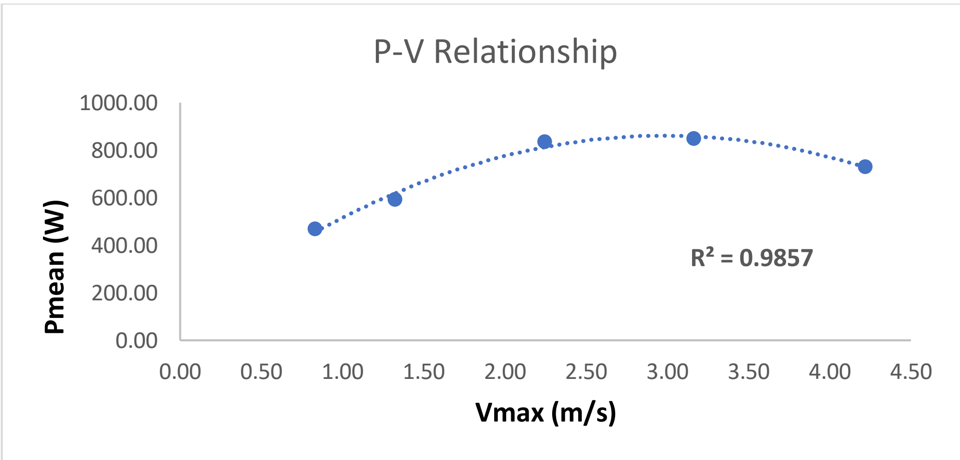

Figure 5. Parabolic P-V relationship at increasing loads during resisted sprints.

Table 2. Descriptive results of performance measures at different loads.

Load	Vmax (m/s)	Pmean (W)	HF (N)
20kg	4.22 ± 0.37	729.56 ± 68.62	155.97 ± 7.47
40kg	3.16 ± 0.45	847.79 ± 141.35	259.33 ± 22.06
60kg	2.24 ± 0.45	835.59 ± 178.87	362.36 ± 16.21
80kg	1.32 ± 0.53	590.75 ± 203.99	443.70 ± 27.13
100kg	0.83 ± 0.29	466.48 ± 160.10	552.79 ± 20.94

Table 3. Descriptive results of F-V variables across the population during resisted sprints.

Variable	Mean ± SD
F0 (N)	846.36 ± 104.38
V0 ($m.s^{-1}$)	58.24 ± 10.13
Pmax (W)	-102.70 ± 22.63
Slope (F0.V0)	846.36 ± 104.38

Table 2 and Table 3 provide a description of the performance variable results used to determine the respective P-V and F-V relationships, respectively. The results of this study find the F-V relationship (Figure 3.) is accurately and near perfectly fitted by linear regressions (R^2= 0.983). The results also found the P-V parabolic relationship (Figure 4.) fitted with polynomial quadratic regressions (second-order) to also be accurate and near-perfect (R^2= 0.986).

Discussion:

The aim of this study was to determine the accuracy of the F-V and P-V outputs of an instrumented sled by assessing the goodness of fit of the F-V and P-V relationships during resisted overground sprinting. The F-V measurements produced from the instrumented sled linearly decreased accurately as the loads increased, while the P-V outputs measured followed the parabolic curve accurately as the loads increased. These findings support the hypothesis that the instrumented sled would be highly accurate in measuring both F-V and P-V outputs within the semi-elite male rugby population (R^2= >0.9). To the authors' knowledge, this study is the first of its kind to determine the accuracy of the instrumented sled to assess F-V and P-V outputs during overground resisted sprinting.

Recent research assessing the goodness of fit of the F-V relationship in elite and semi-elite sprinters during overground sprinting utilising force plates was well fitted by linear regressions (R^2= >0.892).[45,46,47] Results of this study suggest that the accuracy of the instrumented sled as a measurement tool of F-V outputs, presented here as the F-V relationship, is in line with other sprint performance measurement tools such as the gold standard force plates.[47] The F-V results of this study were to be expected on the basis that the methodology was closely aligned to a previous sled tow study that assessed recreational mixed sport (R^2= 0.994-0.999) and elite sprint (R^2= 0.995-0.999) athletes using a radar device finding F-V relationships were well fitted for both populations.[12] These results are of importance as they indicate that an instrumented sled can be used similarly to other advanced measurement technologies for measuring F-V outputs within the semi-elite male rugby population accurately. These findings are promising for strength and conditioning coaches looking for affordable and pragmatic alternatives to mechanically profile athletes during overground sprinting in realistic training and testing environments.

Similar to the F-V relationship, the P-V relationship was also well fitted by second-order polynomial regressions on the expectation that results would be similar to recreational mixed sport (R^2= 0.977-0.997) and elite sprint (R^2= 0.979-0.999) athletes assessed using a radar device.[12] In addition to the above promising results, the goodness of fit for the P-V parabolic relationship is not only aligned with measurements taken from a radar device but also exceeded goodness of fit measurements from force plates comparatively (R^2= >0.732 vs R^2= 0.986 respectively).[46,47] However, it should be noted that the force plate P-V relationship was assessed in an elite sprint trained population with 40m sprint acceleration constructed virtually from several sprints over a 6.6m force plate system embedded into an indoor stadium track surface, and therefore the lower value may be reflective of the computation method of mechanical data.[47] It is important to highlight from the results that the loads used to measure the sprint variables were sufficient within the population to identify the peak of the P-V relationship, further strengthening the certainty of the instrumented sled's ability to accurately measure Pmax, P-V outputs, and other associated mechanical variables.[12]

Although the results of this study are promising, it is limited by the inclusion of non-randomised increases in load for each sprint. However, this methodological approach has been used in previous F-V and P-V studies.[12] Increasing loads over multiple trials are thought to increase absolute error in the F-V relationship as a result of fatigue, potentiation, and variability in movement as identified by Cross, et al.,[41]. Although, the magnitude of this effect is thought to be minimal and therefore was chosen to prevent variability in performance from unexpected loading.[41] Due to time constraints and the number of athletes to test with only one sled available, it was not feasible to use the ideal loading method of %BM, however, this is minimised as absolute loads still provide a sufficient increase to identify the trendline as the load-velocity relationship has been found to be linear.[15] The difference in loading based on position also allowed for BM to be taken into consideration with maximal loading not exceeding 110%BM. This study is the first of its kind, therefore results should be interpreted with caution as they are specific to the male semi-elite rugby population. The results of this study are encouraging for both sports scientists and strength and conditioning coaches as it highlights the potential value of this novel, affordable, and pragmatic technology to measure sprint performance through the mechanical profiling of athletes during overground resisted sprinting. With the increase in popularity of resisted sprinting as a training method and assessment, the availability of measurement technology that more closely replicates sport-specific within-field training provides exciting potential for coaches to undertake testing while minimally disrupting training.

Conclusion:

These results suggest the use of an instrumented sled to determine the F-V and P-V relationships is accurate during resisted sprinting, providing a within-field sport-specific method for coaches to profile individual athlete's sprint performance. The accuracy of the instrumented sled supports the interest of coaches in field sports and their increased need for accessible on-field sport-specific measurement technologies. Future research should focus on determining the reliability of F-V and P-V measures across different loads and populations to strengthen these findings. Research aimed at providing normative data using an instrumented sled would also enable more robust scientific evidence for its use as a resisted sprint assessment and training tool.

Chapter 4:

Force-Velocity Profiles and Optimal Loads of Male Rugby Players during Sled Towing by Position

Prelude:

As previously identified, there is a lack of research regarding the instrumented sled and its use as a practical within-field sprint assessment tool. The results from chapter 3 pertaining to the accuracy of the sled help inform that the instrumented sled is capable of accurately measuring F-V characteristics. Therefore, this chapter is designed to examine whether the device can be used to distinguish F-V profiles and optimal loading strategies for horizontal power production between semi-elite male rugby union forwards and backs.

Abstract:

Recent research into resisted sprinting as a means to assess and improve sprint performance has grown within the rugby union community at all levels. However, little is currently known as to the differences in sprint performance F-V variables between positions in rugby union athletes. This study aimed to compare the F-V profiles and optimal loading for power production between semi-elite rugby athletes (*n*=43) based on their position (forwards vs backs) while providing benchmark sprint assessment data using an instrumented sled. Subjects completed a series of 10-30m maximal effort sprints attached with an instrumented sled at increasing loads ranging from 20-100kgs. The instrumented sled recorded kinetic and kinematic data from the sprint via a load cell. Differences were identified in the F-V profiles of players based on position, however, there was no significant differences in optimal load required for power production. More specifically, significant differences were found with forwards producing higher F0 values than backs ($P \leq 0.02$, ES= -0.75, %difference= 12.4%), as well as forwards producing higher Pmax values ($P \leq 0.01$, ES= 0.82, %difference= 8%). It was hypothesised that forwards would express a more force dominant profile than backs, with higher loads required to optimise power. However, while the findings of this study demonstrate that forwards are more force-dominant than backs, on average, the results highlight that optimal loading is highly individualised for the population, and therefore, an individualised position-specific approach to training prescription and loading is necessary.

Introduction:

Sprinting ability is a fundamental performance indicator for many field sports.[18,31,34,39] Due to the demands of field sports such as rugby, soccer, and hockey, there has been a greater emphasis on improving the sprint qualities of the acceleration phase (0-10m) of sprint performance. Towing a weighted sled while sprinting has grown in popularity as a form of sport-specific resisted sprint training.[2,3] The sled is typically attached to an athlete by a waist or shoulder harness and a tether of various lengths.[33] The overload stimulus is provided by additional weight on the sled in combination with dynamic coefficient of friction between the sled and the surface.[37,42] Sled tow training has been reported to change sprint kinematics and improve sprint kinetics by increasing fast-twitch fibre recruitment, maximal horizontal force output, and maximal horizontal power output (Pmax).[3,10,17,59]

To date, research has sought to determine what sled loads are required to enhance and maximise power production; with optimal loadings varying from 69-96%BM in recreational and sprint-trained cohorts.[12] Other areas of research have focussed on which method of load prescription is most effective for resisted sprint training in an effort to determine a gold standard prescription method.[10,15,34,40,] The methods of load prescription commonly used for sled towing are velocity decrement (Vdec), absolute load, and body mass (BM).[37] However, while all methods appear effective in resisted sprint training, further research is necessary to determine a gold standard method for load prescription.[10,15,37] In addition to the prescription method, a common talking point amongst current researchers is what technology is valid, reliable, and practical for sled tow sprint assessment, and if the results from these assessments can be used to profile athletes force-velocity (F-V) capabilities.[10,15,37,41,42,46] However, there is still a paucity of research to guide appropriate load prescription for an array of sporting populations, with research primarily focussing on recreational and sprint-trained athlete populations.[62]

For rugby union specifically, it is uncommon to exceed sprint efforts of >30m during competition, with sporting rules that result in predominantly performing force-dominant and low centre of gravity movements.[31,34,39,62] At an international level, rugby union athletes are expected to have a high level of proficiency with sprint performance, and as a result, the demand for increased sprint proficiency at regional levels is increasing.[62] In an effort to improve the acceleration phase of sprinting (0-10m), strength and conditioning coaches have turned to resisted sprinting to provide a sufficient stimulus for force, velocity, and power output adaptations.[10] F-V profiling allows strength and conditioning coaches to understand the power output of each individual athlete and identify if they are expressing force or velocity dominance, enabling specific individualised power training. Recent research has provided an initial benchmark for sprint performance and F-V variables using radar and timing light technology in club, professional (regional level, i.e Mitre 10 cup and Super Rugby level), and international level rugby athletes based on position.[65] The results of this study highlighted key differences in sprint speed between playing levels with international players having faster 0-10m acceleration times, professional players having faster 10-20m sprint times, and professional players displaying more force dominant profiles than club and international players.[65]

Positionally, maximal horizontal velocity (Vmax) characteristics increased alongside the increasing positional numbers.[65] Both international and professional players displayed significantly higher profiling values (F0, V0, maximal theoretical power [P0], and Vmax) than club players.[65] However, this study did not include players that sit between club and professional level, those that are in regional level academies representing in regional under 20's and provincial level competition, defined as the semi-elite level rugby players; leaving open a gap in the research. The study does however highlight, how individualised F-V profiling is between positions at different levels and therefore suggests that delivering a single training programme to develop power output during sprinting in rugby athletes would fail to enhance individual's F-V capabilities.[65] It is important for strength and conditioning coaches to understand positional differences in F-V profiling in order to provide individualised and optimised loading for training prescription to enhance an individual's position-specific needs.[65]

Common sprint performance variables assessed include sprint time, split times (early acceleration, acceleration, and braking phases) contact time, F0, V0, Pmax, and GRF.[10,62] These variables are assessed using a range of different technologies independently or used collaboratively including global positioning systems (GPS), timing lights, radar technology, camera's, force plates, and more recently, instrumented sleds.[30] Athletes' F-V capabilities are often profiled through sprinting to determine the mechanical capabilities of each individual's neuromuscular system during multi-joint movement.[46,62] A recent review highlighted that these mechanical capabilities can be accurately measured from sprinting on an instrumented treadmill or overground.[46] However, the review identified gaps in research on F-V measures using more recent technologies and a need for more normative data on different populations using the updated equipment.[46] Research utilising an instrumented sled is scarce due to its recent creation and a limited number of sleds currently built. An instrumented sled is a standard sled with a load cell battery and wireless sender unit attached which can instantaneously measure horizontal force, vertical force, time, and maximal velocity (Vmax) while an athlete performs a resisted sprint. To date, research has successfully measured the F-V relationships during over-ground sprinting using radar devices and force plates on recreational and sprint-trained athletes and enabled the determination of optimal loading for power production within these populations.[12,46,47]

The identified gaps in current research surround a paucity of sled tow research to guide strength and conditioning coaches with load prescription in an array of sporting cohorts, as well as, a general lack of accessible up-to-date technologies to profile athletes in the field. To the author's knowledge, this study is the first of its kind to profile semi-elite male rugby athletes using an instrumented sled and compare the F-V profiles and their optimal loads for power production between positions. The aim of this research is two-fold; first, to compare F-V profiles and optimal loading between forwards and backs, and second, to provide foundational sprint assessment profiling data within the semi-elite male rugby population using an instrumented sled. It is hypothesised that forwards will express a more force dominant profile with higher loads required to optimise power training than backs.

Methods:

Participants

Forty-three semi-elite level male rugby union athletes volunteered to participate in this study. Subjects were split into their respective positional groups of forwards (*n*=25) position 1-8, and backs (*n*= 18) position 9-15. Ethical approval was gained from Auckland University of Technology Ethics Committee (20/345). All subjects provided written informed consent and were aware of all necessary procedures, benefits and risks associated with the study. Subjects were required to be over 18 years of age, have been selected to represent at regional level (i.e regional U20's competition), and have a minimum of two years rugby training experience. It was required that all subjects be in good health at the time of testing with no known performance restricting illness, disease, or chronic and acute injuries. Subjects were required to be injury-free (>3months prior to testing). Subjects were required to have some sort of training history with resisted sprinting.

Table 4. Descriptive data of subjects by position presented as mean ± standard deviation (SD).

Position	Forwards	Backs	Sig.
Age (y)	19.80 ± 1.60	19.20 ± 1.70	0.23
Body weight (kg)	112.83 ± 11.66	90.11 ± 10.08	<0.01**
Height (m)	187.19 ± 6.47	180.71 ± 6.71	<0.01**

**Significant difference between height and weight between forwards and backs (*P*<0. 001).

Design & Procedures

A cross-sectional experimental approach was used to examine the differences in F-V profiles and optimal loading between semi-professional rugby players by position. Testing procedures were completed indoors on a turfed track to control the environment. Subjects were instructed to wear their typical training clothing which included their rugby boots. Subjects had been split into groups of 3-6 allowing adequate rest time between sprint trials of no more than five minutes active rest. The division of groups into 3-6 subjects allowed for testing to be undertaken during the Covid-19 pandemic while appropriately following the current Covid-19 restrictions. Subjects completed a ~13-minute warm-up prior to testing consisting of foam rolling, band stretches, jog-specific dynamic exercises, and 20m sprint accelerations at 75, 80, 85-90, 95, and 100% sprint pace. A specific familiarisation process was not undertaken as subjects were already familiar with various forms of resisted sprinting from trainings. Subjects were in a pre-season training phase. Subjects were required to complete three to four resisted sprint trials of varying distances between 10-30m with a heavy-duty instrumented sled attached at the waist via a 5m nylon tether. Loading for each trial was progressive and non-randomised. Load selection varied depending on the position and weight of each subject varying from 20, 25, 40, 50, 60, 75, 80, or 100kg's to allow for BM to be taken into consideration (20, 25,40, 50, 60, 75, 80kg for backs, and 25, 40, 50, 60, 75, 80, 100kg for forwards). Subjects were required to start with their feet behind a line and in a three-point stance with tension applied on the tether. Subjects were given a verbal que as to when they could begin the sprint in their own time. Subjects were asked to sprint as hard and as fast as they could for as long as they could, stopping when they felt a significant decline in momentum. This ensured that maximal efforts were given for each trial resulting in the varying sprint distances of 10-30m.

Equipment & Data Analysis

The assessment of sprint performance was performed using an instrumented sled. The instrumented sled is a custom-built force and speed measurement device. It contains a load cell (250kg S-Beam load cell, Millennium Mechatronics, Auckland, New Zealand) that measures the pulling force between the subject and the sled. The instrumented sled used was constructed out of folded steel framing and flat railings that lay flush with the ground surface (5.64kg: GetStrength, Model: HT 50mm Sled, Auckland, NZ). Attached to the front of the sled is an accelerometer (3-Axis Digital Accelerometer, Analog Devices, Massachusetts, USA) to measure the acceleration of the sled. Data from the sled was wirelessly transmitted to a laptop at a sample rate of 1000Hz during a trial. The sled was loaded with a varying number of 20kg calibrated Olympic-style lifting plates (Model: PL Comp Discs, Eleiko Sport, Halmstad, SWE).

Force and accelerometer data were processed using a fourth-order low pass Butterworth filter with a cut-off frequency of 15Hz and 5Hz, respectively (selected via residual analysis).[67] Accelerometer data was integrated to calculate velocity-time data. Velocity data was then modelled to fit the inverse exponential function of the velocity-time relationship using the previously validated least squares method.[12,66] The analyses were performed using MATLAB R2021a (MathWorks, Massachusetts, USA). The F-V and P-V relationships were assessed using kinetic data (peak horizontal force (HFpeak), mean horizontal power [Pmean], and Vmax) produced from the resisted sprint trials averaged over 10 steps during the maximum velocity phase. F0 and V0 were both calculated from the F-V and P-V relationships of the sprint trials of each individual and were determined by the X and Y intercepts.[65] The slope (F0.V0) was determined by the trendline after plotting HFpeak against Vmax with each load.

The optimal load was determined using the P-V curve and identified as the combined sled mass when peak power was achieved.

Statistical Analysis

All statistical analyses were performed using SPSS software (version 25) and Microsoft Excel (version 2106). Descriptive data from the subjects are presented as mean ± SD. The data was explored using histogram plots, and the normality of the distribution for all variables were tested using Shapiro-Wilk's test. Homogeneity of variance will be tested using the Levene's test. Independent two-tailed t-tests were conducted to determine between-group differences. Effect sizes (ES) were determined for each group and interpreted using Cohen's *d* threshold definitions of trivial (<0.2), small (0.2), medium (0.5), and large (0.8).[68,70] This is presented as mean differences and 95% confidence intervals, significance was set at an alpha level of p <0.05.

Results:

Significant differences were found between forwards and backs for F0 and Pmax ($P \leq 0.02$). F0 was significantly higher in forwards in comparison to the backs ($P \leq 0.02$, ES= -0.75, %difference= 12.4%). Pmax values were significantly higher in the forwards also when compared to the backs ($P \leq 0.01$, ES= 0.82, %difference= 8%). V0, Slope, and optimal loading for power both showed small to moderate differences between groups, however, this did not meet acceptable significance levels.

Table 5. Comparison of averaged F-V profile variables between forwards and backs.

Variable	Forwards	Backs	ES	Sig
F0 (N)	714.73 ± 103.68	626.09 ± 134.10	-0.75	0.02**
V0 ($m.s^{-1}$)	5.74 ± 0.54	6.04 ± 0.55	0.56	0.09
Pmax (W)	1025.19 ± 176.07	941.62 ± 190.10	0.82	0.01**
Slope (F0.V0)	-124.00 ± 22.15	-102.58 ± 27.79	-0.46	0.16
Optimal Load (kg)	63.04 ± 16.82	55.06 ± 12.07	-0.55	0.11

** Significant at *P*=<0.05.

Discussion:

The aim of this study was to compare sprint F-V profiles and optimal loads between the forwards and backs of semi-elite rugby union athletes. The results of this study show that significant differences do exist between forwards and backs, primarily in F0 and Pmax measures. It was hypothesised that we would see significant differences in force measures between forwards and backs which was found to be true for this population with forwards expressing higher F0 than backs (F0= $P \leq 0.02$, ES= -0.75). However, the expectation of forwards would require a significantly higher load to optimise power is not accepted for this study.

One of the main effects identified across the two positional groups was the difference in F0. As expected, forwards expressed significantly higher F0 values than backs, which is consistent with current research which identifies forwards as being more force dominant than backs.[65] This is likely indicative of the differences in performance demands with forwards involved in a larger number of high force movements (i.e rucks, scrums, and mauls).[62,65] It should also be highlighted the significant difference in body weight (BW) between the forwards and backs (112.83 ± 11.66 vs 90.11 ± 10.08, P= <0.01) with forwards being significantly heavier than the backs, which will likely influence the force production capabilities in favour of the forwards. [65,71] Research into positional differences amongst rugby players at different levels highlighted that at all levels and across all positions, forwards had more force dominant profiles than backs.[65] It was of particular interest in that study that although the loose forwards were found to have similar Vmax characteristics as inside backs, they still had a much more force-dominanted profile than the backs.[65] This result further supports the notion that forwards have more force-dominant profiles than backs despite similarities in other profiling variables and sprint characteristics, highlighted by the influence of differing positional physical attributes and demands.[65]

This study also found a significant difference in Pmax between the forwards and backs ($P \leq 0.01$, ES= 0.82). As Pmax is an expression of the combination of force and velocity, it is somewhat expected that with significant differences shown between groups in F0 that there is a significant difference in Pmax due to the influence of F0. Interestingly, V0 expressed moderate differences between the forwards and the backs (ES=0.56), however, this between-group difference was not considered significant. These results may suggest that overall, semi-elite rugby athletes are expressing a more force dominant F-V. These results seemingly are in line with the recent research by Watkins, et al.[65] which investigated positional differences between club, professional and international rugby athletes; the findings suggested international athletes expressed significantly higher F0, V0, maximal theoretical power (P0), and Vmax measures compared to club level athletes, while professional athletes expressed significantly higher F0 and P0 measures with similar V0 and Vmax compared to club-level athletes.[65] These results suggest that positional differences in V0 tend to be more significant at elite-level rather than semi-elite level while supporting the significant positional differences in F0 and Pmax at a semi-elite level. The results aligning with what is current research for the semi-elite population also brings further confidence for the use of an instrumented sled as a sprint measurement tool.

Similar to V0, the optimal load for each group to enhance power presented with moderate yet non-significant differences between forwards and backs (ES=-0.55). This is likely due to the individualised nature of each F-V profile within semi-elite athletes, as highlighted by the range in individual's optimal loads for forwards (36-100kg) and backs (31-71kg). An interesting observation of this study to consider is when optimal load is expressed relative to BW. Optimal loading for forwards sat at an average of 55.9%BW, while the relative optimal load for backs was an average of 61.1%BW (ES=0.37). This differs from current research within recreational and sprint-trained athletes which previously suggested that optimal loading to optimise power likely sits between 69-96%BW, further highlighting how individualised power profiling is to each sport, and a need for future research to determine optimal loading for a range of sporting cohorts and their competition levels.[12] However, this is only speculative and potentially influenced by different surface types, therefore, further research should be considered in this area.

Although this investigation is the first of its kind to compare F-V profiles and optimal loads taken from an instrumented sled, there are some limitations. The smaller sample size used for this study in comparison to Watkins et al.[35] (n=176) meant that comparisons between groups was limited to positions being grouped as forwards and backs as opposed to more specific positional groups (e.g loose forwards, midfield backs) which may have influenced the results. Non-randomised increases in load were used which may increase the absolute error in F-V results as a result of potential fatigue, potentiation, and movement variability. However, this method has been used in previous research and was chosen as it was not feasible to use %BM and mitigated variability in performance from unexpected loading.[12,41] The results of this study should be interpreted with caution as reliability testing is yet to be performed using the instrumented sled as a measurement tool for F-V and P-V profiling. This study was restricted in its ability to undertake test-retest reliability testing due to the Covid-19 restrictions at the time of testing preventing repeat testing within an acceptable time frame. Future research should seek to determine the reliability of the instrumented sled as a sprint performance measurement tool. It is important for research to continue to be built upon to be able to quantify optimal training loads at different levels within rugby. It may also be of interest for future research to investigate F-V profiles at club and semi-elite levels to determine why differences in V0 are non-significant within these populations compared to elite athletes.

Conclusions:

The F-V and optimal loading results of this study may be of use to guide strength and conditioning coaches in determining effective training by providing foundational data as a benchmark for forwards and backs. F-V profiling and optimal loading results suggest that within the semi-elite rugby population, forwards appear to be significantly more force dominant than backs. The forwards produced significantly higher Pmax values compared to the backs with this likely due to their increased involvement in force and power dominant movements such as rucks, scrums, and mauls. These results give an indication as to the current sprint qualities of semi-elite rugby athletes. At semi-elite level, it is important that each individual should be assessed and profiled individually in order to prescribe appropriate loading to optimise power production.

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Chapter 5:

Discussion, Conclusion, and Practical Applications

Prelude:

As the previous chapters included their own separate discussion and conclusion paragraphs, this chapter focuses on synthesising the main findings across all chapters of the thesis. As part of the investigative process, it is important to acknowledge the main limitations of this thesis. From this synthesis, the key practical applications within strength and conditioning training and assessment are highlighted to help guide strength and conditioning practice. Alongside the practical applications, recommendations for future areas of research are provided in an effort to guide and promote further development of research in sled towing, F-V profiling, optimal loading, and practical usage of an instrumented sled.

Discussion:

Summing up the investigative process, the thesis has provided insight into the utility of the instrumented sled as a novel sprint performance assessment tool. The thesis was able to 1) compile and evaluate technologies and methodologies in current field-sport sled tow literature; 2) establish the accuracy of the instrumented sled's ability to measure F-V and P-V measures from overground sprinting; 3) compared mechanical variables and optimal loads between semi-elite rugby union athletes by position using the instrumented sled.

Sprint qualities are a critical indicator of performance in many field sports.[19,62,65] Resisted overground sprinting is an increasingly popular method of sprint performance training and assessment.[15] The review into current sled tow literature within field and court sport athletes highlighted discrepancies in the methodologies and technologies used to ascertain appropriate training loads and determine mechanical properties. Recent research investigating load prescription methods have typically utilised absolute loads, body mass (%BM), and velocity decrement (%Vdec).[7,15,31] All methods of load prescription were based on the load-velocity (L-V) relationship which is expressed as a parabolic relationship during sled towing, as load increases velocity will decrease. However, Vdec is argued as the most precise method for optimising load for power production as it takes into consideration body mass and strength capabilities with a range of 48-52%Vdec for optimised power production versus the %BM method of which optimal loading ranged from 69-96%BM.[7,12,15,31] However, due to between-study differences in methodology used to prescribe %Vdec these studies are not directly comparable, therefore, no direct conclusion can be drawn as to which method is better for targeted power production.[10,37] These discrepancies appear to be from a general paucity of research within field sports using resisted sled towing, which is likely due to its recent rise in popularity ahead of research. Within the studies reviewed, a variety of measurement tools were used to determine mechanical capabilities during overground sprinting; including radar devices, timing lights, force plates, and global positioning systems (GPS). The general consensus was that these technologies were all accurate in measuring the mechanical force-velocity (F-V) capabilities from the mid acceleration phase onwards (>10m) with force plates identified as being the gold standard measurement technology.[26.27.28,31,45,46,47] It was noted that amongst all technologies that there was a gap in the ability for any of the technologies to accurately measure early acceleration kinetics (<5m). [26.27.28,31,45,46,47] Although force plates have been determined as a gold standard for sprint performance assessment, they are expensive and impractical for in-field use in field sports and during sled towing.[31] Therefore, highlighting a need for updated, practical, in-field technologies to be developed and trialled for the assessment of sprint performance variables.

Current sprint performance assessment has often used a number of different technologies and/or combinations of technologies.[30,46,50,65,73] However, it has not always been practical for strength and conditioning coaches to access and use these within the field.[31] With an identified need for an accessible technology within strength and conditioning practice, a new assessment tool has been introduced to fill the gap (i.e., instrumented sled). Technologies created for the purpose of sprint performance assessment requires rigorous testing to determine usability within strength and conditioning practice and research settings.[72] Therefore, the third aim of this thesis sought to determine the accuracy of the instrumented sled's ability to measure F-V and P-V relationships. The main results from this investigation found that both the F-V (R^2= 0.983). and P-V (R^2= 0.986) relationships were accurately and near perfectly fitted by linear and second-order polynomial quadratic regressions in semi-elite male rugby union players, respectively. This result aligns with other technologies such as radar devices which were accurate in profiling the F-V relationships in recreational (R^2= 0.977-0.997) and sprint trained (R^2= 0.979-0.999) athletes, as well as the P-V relationship R^2= 0.994-0.999 and R^2= 0.995-0.999, respectively.[12] Although there were differences in the computation method, accuracy results for the instrumented sled were stronger than the gold standard force plates for both F-V (R^2= >0.732) and P-V (R^2= 0.986) relationships in sprint trained athletes.[47] These results are promising and provide confidence that the instrumented sled may be a practical solution for strength and conditioning coaches to use as an accurate on-field sprint assessment tool.

The final study (Chapter 4) looked to build upon the promising results of the instrumented sled being an accurate sprint assessment tool by testing the sled's discriminative ability.[72] The aim of the study was to test the discriminative ability of the instrumented sled by comparing the F-V profiles and optimal loads of male rugby players by their position. To date, only one other known study has investigated the F-V profiling differences in male rugby players by position and by playing level using a radar device and timing lights.[65] Watkins, et al.[65] study compared club, professional, and international players, however, they did not compare the optimal loading ranges of rugby players that sit between club and professional level, the semi-elite who predominantly represent at provincial level.[65] The results of this study (Chapter 4) found significantly higher F0 values in the forwards compared to the backs ($P \leq 0.02$, ES= -0.75, %difference= 12.4%), as well as higher Pmax values in the forwards ($P \leq 0.01$, ES= 0.82, %difference= 8%). Notably, there was significant differences in bodyweight (BW) with forwards being significantly heavier (112.8 ± 11.7 vs 90.1 ± 10.1, P= <0.01). This likely would have influenced the force production capabilities in favour of the forwards.[65.71] These findings support Watkins, et al.[65], who found higher F0, V0 maximal theoretical power (P0), and Vmax values in forwards versus backs at international level and higher F0 and P0 values in forwards at professional level compared to the backs; Therefore, at international, professional, and semi-elite level rugby union forwards appear to display significantly greater F0 and Pmax compared to backs.[65] With the results of this study aligning with current research, there is further confidence brought to the instrumented sleds use as a sprint performance assessment tool due to its ability to discriminate between groups (forwards vs. backs). Other findings of interest from this study include the differences in optimal loads between groups. Although not significant, moderate differences were seen in optimal loads (ES=-0.55). This is likely due to the individualised nature of each F-V profile which can be seen in the individual ranges of optimal loads for forwards (36-100kg) and backs (31-71kg). In addition to this and in relation to optimal loads expressed relative to BW, optimal load ranges for the population sat at an average of 55.9%-61.1%. This differs from current optimal load ranges in current research which determined optimal loading to enhance power likely sits between 69-96%BW in a range of recreational and sprint-trained athletes[12] This suggests that power profiles vary widely between sports and individualised power profiling should be conducted relative to the sporting domain. Future research should aim to identify optimal load ranges for horizontal power production in athletes across different athlete cohorts.

Limitations:

The thesis presented does carry methodological limitations and constraints. These limitations should be taken into consideration when interpreting the results presented in the thesis. Reasoning and justification of each limitation has been provided in the following:

1) One of the primary limitations apparent in both investigative studies is the use of non-randomised progressive loading. This decision was made to minimise the introduction of error potentially caused by subjects not being able to judge the increase or decrease in load from the previous trial and therefore, potentially affecting their performance or causing a mistrial. It

is possible that that error has been introduced due to the potential influence of fatigue and potentiation as loads increased. However, this method has been adopted in similar research as practically needed.[12,41]

2) Both investigative studies were limited by the Covid-19 pandemic and the NZ Government restrictions placed on the country at the time of data collection. With the thesis following a clinimetric framework, attempts were made to undergo two data collections one week apart in order to present test-retest reliability. However, the city where data collection took place went into lockdown the week of the original data collection data resulting in the initial data being collected on the date for the second data collection. Two consecutive attempts were made one then two weeks after the original data collection, however, the city went in and out of lockdown on both occasions. Therefore, only accuracy and discriminative ability results could be presented for this thesis.

3) In order to follow Covid-19 restrictions, subjects were required to attend testing in groups of six or less. This created time constraints for data collection and therefore, it was not feasible to incorporate %BM as part of the load prescription methodology to take into consideration differences in physical attributes between subjects. However, this was mitigated by using different absolute loads between backs (20-80kg) and forwards (40-100kg). The absolute loads relative to body weight were very similar on average between groups with backs averaging 109.5%BM and forwards averaging 108.6%BM. This did not exceed 110%BM which has been used in previous literature.[12,38]

4) As the investigative studies are the first of its kind to test the instrumented sled using subjects, there was no existing research to draw direct comparisons to. This is seen as completely unavoidable and therefore, comparisons drawn between the results of these studies and previous research should be interpreted with caution.

5) As previously mentioned, Covid-19 impacted the ability for test-retest reliability to be investigated for measurements produced by the instrumented sled. Therefore, the results of Chapter 4 should be interpreted with caution.

Conclusion:

The presented thesis was successful in its aim to evaluate and compile current sled tow literature methodologies and technologies. This provides ease of access to current sled tow practices for both strength and conditioning coaches, students, and researchers. Strength and conditioning coaches need to take into consideration positional differences in rugby union with significant differences apparent in the F-V profiles of forwards and backs with forwards displaying more force dominance and higher maximal horizontal power production than backs.

In regards to optimal loading, it is apparent that optimal loading for power production differs for a range of cohorts indicating a need for individualised training zones to be determined. With the thesis following a clinimetric framework for the assessment of the instrumented sled, it is acknowledged that not all aspects of this approach were able to be presented in the thesis due to limiting circumstances. However, the thesis has successfully presented two of the four fundamental clinimetric properties to assessment testing determining near-perfect accuracy and discriminative ability of the instrumented sled. This is highly valuable in the development of the instrumented sled as a sprint performance measurement tool and brings about confidence in its implementation in strength and conditioning research and practice.

Practical Applications and Future Research:

- The identification of force-dominant F-V profiles in semi-elite rugby forwards aligns with current research at professional and international levels. These results further support the notion that force production is heavily influenced by physical attributes and positional demands in rugby union. This information can help guide strength and conditioning coaches by providing a benchmark for positional groups at the semi-elite level and providing training direction.
- The optimal loading characteristics were lower than previously reported ranges in differing populations. Optimal loads recommended for semi-elite rugby union strength and conditioning coaches to use is 55.9% for forwards and 61.1% for backs. This indicates a need for optimal loading to remain individualised for each population in order to train in the appropriate zone. Future research should continue to expand on this area by determining optimal loading characteristics for other sporting cohorts.
- With the instrumented sled being an accurate measurement tool for sprint performance assessment, future research should sought to determine the reliability and sensitivity to change of F-V and P-V measures from the instrumented sled.
- To date, no sprint performance measurement technology or methodology has been able to accurately provide feedback of the sprint variables associated with first-step quickness/early acceleration. Future research should look to determine if any current accessible technologies are able to provide this information accurately and reliably, as this would provide significant insight required for appropriate and targeted training to enhance sprint performance.
- Within sled tow research, there is a paucity of research to guide appropriate load prescription for an array of sporting populations. Research has primarily focussed on recreational and sprint-trained athletes, therefore, future load prescription research should look to use a range of sporting cohorts to provide foundational load prescription guidelines to help guide strength and conditioning coaches.

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Appendices:

Appendix 1. Ethics Approval and Amendments from AUTEC

TE WĀNANGA ARONUI O TĀMAKI MAKAU RAU

26 November 2020

Matt Brughelli
Faculty of Health and Environmental Sciences

Dear Matt

Re Ethics Application: **20/345 Relationships between horizontal force output during sled towing and 30m sprint acceleration characteristics in male rugby players**

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

Your ethics application has been approved for three years until 23 November 2023.

Non-Standard Conditions of Approval

1. Update the title on the Consent Form to include males;
2. Update the name of the Executive Secretary to Dr Carina Meares.

Non-standard conditions must be completed before commencing your study. Non-standard conditions do not need to be submitted to or reviewed by AUTEC before commencing your study.

Standard Conditions of Approval

1. The research is to be undertaken in accordance with the Auckland University of Technology Code of Conduct for Research and as approved by AUTEC in this application.
2. A progress report is due annually on the anniversary of the approval date, using the EA2 form.
3. A final report is due at the expiration of the approval period, or, upon completion of project, using the EA3 form.
4. Any amendments to the project must be approved by AUTEC prior to being implemented. Amendments can be requested using the EA2 form.
5. Any serious or unexpected adverse events must be reported to AUTEC Secretariat as a matter of priority.
6. Any unforeseen events that might affect continued ethical acceptability of the project should also be reported to the AUTEC Secretariat as a matter of priority.
7. It is your responsibility to ensure that the spelling and grammar of documents being provided to participants or external organisations is of a high standard and that all the dates on the documents are updated.

AUTEC grants ethical approval only. You are responsible for obtaining management approval for access for your research from any institution or organisation at which your research is being conducted and you need to meet all ethical, legal, public health, and locality obligations or requirements for the jurisdictions in which the research is being undertaken.

Please quote the application number and title on all future correspondence related to this project.

For any enquiries please contact ethics@aut.ac.nz. The forms mentioned above are available online through http://www.aut.ac.nz/research/researchethics

(This is a computer-generated letter for which no signature is required)

The AUTEC Secretariat
Auckland University of Technology Ethics Committee

Cc: kristyearnshaw1@hotmail.com; aaron.uthoff@aut.ac.nz

Appendix 2. Ethics Approval and Conditions from MSAP

NEW ZEALAND RUGBY

03 May 2021

Kristy Earnshaw
By Email: kristyearnshaw1@hotmail.com

Medicine and Science Advisory Panel Decision Letter

Re. Principal Researcher: Kristy Earnshaw
Study Title: "Relationships between horizontal force output during sled towing and 30m sprint acceleration characteristics in male rugby players"

Dear Kristy,

I am pleased to inform you that the Medicine and Science Advisory Panel (MSAP) for New Zealand Rugby (NZR) has reviewed your proposal and would like to provide its approval for the above proposed study.

This approval is conditional upon approval from Auckland Rugby Union; the receipt of a signed data collection agreement (**attached**) and upon secure storage of the data being collected in https://nzru.sharepoint.com/:f:/s/MedicalandScienceAdvisoryPanel/EoBms-hWIvhJuGbdbr91SLIBBp3komkzw62q2BkJe5E7DA?email=kristyearnshaw1%40hotmail.com&e=R2UJSC

At the conclusion of your study please provide MSAP with a report of your findings. This report will be passed along to relevant parties in NZR to ensure that this research is disseminated across the organisation.

If you require anything further or if we can be of assistance, please contact us via email msap@nzrugby.co.nz.

Kind regards,

Lauren Richardson
MSAP Coordinator

On behalf of the Medicine and Science Advisory Panel

Appendix 3. Participant Information Sheet

TE WĀNANGA AR
O TĀMAKI MAKAU

Participant Information Sheet

Date Information Sheet Produced:

7th October 2020

Project Title

Relationships between horizontal force output during sled towing and 30m sprint acceleration characteristics in male rugby players.

An Invitation,

Hi, my name is **Kristy Earnshaw** - I am a Masters student at AUT University. I would like to personally invite you to participate in our project that aims to determine the relationships between horizontal force output during sled towing and 30m sprint acceleration characteristics in rugby players.

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

What is the purpose of this research?

In the field of strength and conditioning, a recently explored method of training for sprint acceleration is resistance sprint training utilising a weighted sled. Currently, there is little research around how instrumented sled towing variables at different loads relate with 30 m sprint variables. Such information could help to inform prescription of sled tow loads for optimal horizontal force production adaptations. This research may enhance the understanding of the relationships between sled load variables and characteristics of sprint force-velocity profiles in rugby players. The purpose of this research is two-fold, primarily to determine if horizontal force output during heavy and light sled towing significantly correlate with force-velocity profile variables during an unresisted 30m sprint, and to determine test-retest reliability of horizontal force outputs during heavy and light sled towing.

The findings of this research may be used for academic publications and presentations.

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

Your team/training group was identified for a presentation by the lead researcher on the study outline and requirements of participation, in the effort of recruiting applicable athletes into testing. You are eligible to participate in this study if you are (1) a male between the ages of 18 and 35 years; (2) have >2 years of rugby training experience; (3) are free from disorder, or acute/chronic injury at the time of testing occasion (>3 months injury-free, and (4) satisfy the minimum requirements for respective sporting code (rugby athletes = played at academy level or above).

Your team has been selected as you fulfil baseline requirements of being male rugby players with 2 or more years' experience playing rugby.

How do I agree to participate in this research?

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

Please note: If you have and/or suffering from heart disease, high blood pressure, any respiratory condition (mild asthma excluded), any illness or injury (<3months) that impairs your physical performance, any infection, or are outside the limits of the required age range of 18 to 35 years, you will be excluded from this study.

Your participation in this research is voluntary (it is your choice) and whether or not you choose to participate will neither advantage nor disadvantage you. You are able to withdraw from the study at any time. If you choose to withdraw from the study, then you will be offered the choice between having any data that is identifiable as belonging to you removed or allowing it to continue to be used. However, once the findings have been produced, removal of your data may not be possible.

What will happen in this research?

Once you have decided to participate in the study you will be asked to complete a maximum 2-hour testing session either at the AUT-Millennium track or at one of the regular Auckland Rugby Union training fields (based on suitability of surface), and for a select few (10 participants) repeat identical study procedures 7 days following the initial testing occasion (if able). Participants will be randomly divided into groups of 5-7 for testing in order to minimise testing time. The study procedures are as follows:

Initially, height and body weight will be measured and/or most recent measures collected from Auckland Rugby Union. Following this, a complete verbal explanation of the testing procedures and equipment will occur, followed by a standardized lower-extremity dynamic warm-up for 10 minutes. The warm-up will be completed by submaximal 'stride-outs' of sprints performed. The testing procedures will consist of maximal sprints performed under a selection of resisted sled loads. Specifically, you will perform two trials of 30m sprints while towing a selection of 5 randomized loads (unloaded, 25, 50, 75, and 100kg) interspersed with 10-minute passive rest periods (i.e. ten sprints in total). It is possible that collection may occur with multiple test subjects in one instance.

If you wish to continue your participation, you will be invited to return to our testing facilities where the first 10 responders will undertake a second testing session seven days later at the same time of day. This session will follow the same procedures as the first testing session to determine the reliability and validity of the test variables.

What are the discomforts and risks?

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

How will these discomforts and risks be alleviated?

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

What are the benefits?

Each participant will receive a personalised athletic assessment regarding their sprinting performance. This will include individualised force-velocity profiles and sprint split times upon request. This information can be used to provide further insight into your personalized training recommendations, and you may wish to share these results with your coaches to increase their understanding of where your sprint performance is currently. The researcher will benefit also, given that this is a novel, applied research study. The researcher will gain valuable knowledge, experience, and insight into the acute effects of sled tow at given loads. The results of this research are intended to be published through submission to peer-reviewed journals to contribute and grow industry knowledge. New knowledge for researchers and practitioners will be gained looking into the ability to profile optimal load for development of peak power in force and velocity dominant sprint athletes. Exploring this area of research would enable the strengthening of current research surrounding sled tow loading and their applicability in acceleration training. Understanding the potential relationships may also increase knowledge to help guide strength and conditioning coaches in programming for sprint acceleration improvement using sled tows and F-V profiling. The findings may have strong implications regarding exercise prescription for athletes in New Zealand.

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

What compensation is available for injury or negligence?

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

How will my privacy be protected?

Testing procedures and subsequent data collection may occur in small groups, therefore confidentiality during this period will be limited between those performing sprinting within the same session. No results will be shared during the testing occasion; therefore, your individual data will be protected and anonymous from other participants in your testing group. Outside of the testing occasion, your privacy will be protected by data being de-identified (an athlete code instead of name; e.g. 30m unresisted_A1), and the researcher will not disclose anyone's participation in this study. No names or pictures will be used in reporting (unless the participant gives explicit additional written consent for media purposes following AUT protocols and organised via the AUT university relations team). During the study, only the applicant and named investigators will have access to the data collected. The results of the study may be used for further analysis and submission to peer-reviewed journals or submitted at conferences. To maintain confidentiality, in all publications resulting from this research participants' data will be averaged and represented as group means.

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

What are the costs of participating in this research?

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

What opportunity do I have to consider this invitation?

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

Will I receive feedback on the results of this research?

Yes, upon completion each participant will gain a personalised athletic assessment regarding their sprinting performance. It is your choice whether you share this information with your coach or other people.

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

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

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

Whom do I contact for further information about this research?

Please keep this Information Sheet and a copy of the Consent Form for your future reference. You are also able to contact the research team as follows:

Researcher Contact Details:

Kristy Earnshaw, kristyearnshaw1@hotmail.com

Project Supervisor Contact Details:

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

Approved by the Auckland University of Technology Ethics Committee on *26/11/2020*, AUTEC Reference number *20/345*.

Appendix 4. Consent Form

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

Project title: *Relationships between horizontal force output during sled towing and 30m sprint acceleration characteristics in rugby players.*

Project Supervisor: *Dr Matt Brughelli*

Researcher: ***Kristy Earnshaw***

- ○ I have read and understood the information provided about this research project in the Information Sheet dated 6th October 2020.
- ○ I have had an opportunity to ask questions and to have them answered.
- ○ I understand that I may withdraw myself or any information that I have provided for this project at any time prior to completion of data collection, without being disadvantaged in any way.
- ○ I am not suffering from any current injury, illness, or disorder that may impair my ability to perform the required tasks nor am I outside the limits of the required age range of 18 to 35 years.
- ○ I agree to answer questions and provide physical effort to the best of my ability throughout testing.
- ○ I agree to take part in this research.
- ○ I consent to the indefinite storage of my de-identified data for re-analysis, should future similar uses arise.
- ○ I wish to receive a copy of the report from the research (please tick one): Yes○ No○

Participant's signature: ....

Participant's name: ....

Participant's Contact Details (if appropriate):

....

....

....

....

Date:

Approved by the Auckland University of Technology Ethics Committee on _*26 November 2021*_ AUTEC Reference number 20/345