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Evaluating methodology and technology of sled tow studies in field sport athletes: a narrative review

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A B S T R A C T

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. This increase in sled tow popularity has resulted in an abundance of literature that highlights the discrepancies around load prescription volume, intensity, and methodology. To date, sled tow reviews have focused on the usefulness of weighted sled towing as a form of resisted sprint training when in comparison to unresisted sprint training. The purpose of this review is to identify and discuss the different technologies and methodologies used to assess sled tow sprinting and their associated performance variables and provide practical considerations for coaches who wish to utilise these methods of training and sprint assessment. This review outlines current sled tow literature and methodological approaches, with an emphasis on how different technologies and application of methodology are used and how they affect outcome variables. Furthermore, the review aims to assist industry practitioners with their current understanding of resisted sled tow sprinting application, while highlighting a need for future research to streamline methodological approaches and develop technological advances to accurately measure and report acceleration phase variables.

1. Introduction

Sprint performance is a fundamental capability for success in field-sports (Carlos-Vivas et al., 2019). Resistance training exercises are commonly used to improve sport specific sprint performance capabilities (Young et al., 2001). Due to the stop start nature of running and sprinting 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 (Carlos-Vivas et al., 2019; Macadam et al., 2017; Pantoja et al., 2018; Young et al., 2001). Common forms of applied resistance sprinting include sled tows, parachutes, resistance bands, and weighted vests (Gil et al., 2018). 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 (Carlos-Vivas et al., 2020).

Resisted sprint testing can allow strength and conditioning coaches to assess and profile individuals' force-velocity (F-V) capabilities. The variables which testing often looks to assess and characterise F-V capabilities include theoretical force and velocity production as a result of resisted sprint training (Pantoja et al., 2018). Resisted sprinting improves sprint maximum force output (F_{max}), theoretical maximum force (F0), theoretical maximum velocity (V0), and maximal power output (Pmax) (Pantoja et al., 2018). F0 and F_{max} 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 (Pantoja et al., 2018). Using an athlete's F-V profile allows coaches to monitor changes to the above performance variables through increasing neural activation, recruitment of high-threshold motor units, and horizontally oriented force output, contributing to an overall improvement in the F-V profile

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(Macadam et al., 2016; Monte et al., 2017). 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 (Van Den Tillaar et al., 2018). Therefore, training methods that are sport-specific, progressive, and require high strength demands are ideal for developing sprint acceleration within field-sports (Cahill et al., 2019).

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 (Cahill, Cronin et al., 2019; Carlos-Vivas et al., 2020; Macadam et al., 2016; Pantoja et al., 2018). 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) (Carlos-Vivas et al., 2020; Macadam et al., 2016; Pantoja et al., 2018). Light sled tow loads have conflicting results with some sources finding improvements in sprint performance through increases in V0 and Pmax >30m, while others have found no significant difference between light resisted and unresisted sprints (Cahill, Cronin et al., 2019; Carlos-Vivas et al., 2020; Petrakos et al., 2016). When it comes to optimal loading to improve sprint acceleration, the general consensus is that heavy loads are better than light loads, 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 (Cahill, Cronin et al., 2019; Carlos-Vivas et al., 2020). 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 (Cahill, Cronin et al., 2019; Carlos-Vivas et al., 2020; Murray et al., 2005). These discrepancies suggests that there is a gap in the research surrounding the differing measurement tools and methodologies used in sled tow research. This leaves practitioner/coach guidelines remaining unclear as to what technology and methodologies are most appropriate for athlete testing and monitoring.

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.

A total of 12 articles met the inclusion criteria for this review. From the research included, it was evident that there was a variety of methods utilised to assess 5-45m sled resisted sprint variables, including common use of timing lights and radar device. Sled load prescription varied across articles with the most common methods used being %BM and %Vdec. The common variables measured in the research included Pmax, maximal velocity (Vmax), ground reaction forces (GRF), F0, V0, and Vdec. The research primarily focuses on the acute effects of sled tow with limited studies undertaken longitudinally with field-sport athletes. Sled tow sprinting research has been undertaken within a variety of different field-sports with rugby union and soccer being the most common. This is perhaps due to the sport-specific overload that sled tow sprinting provides with the stimulus primarily targeting the early acceleration phase of sprinting which is prioritised over maximal velocity sprinting within these two sports (Pantoja et al., 2018; Young et al., 2001).

2. Literature Search Strategy

To conduct 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. Boolean operators were used during keyword searches. The reference section of articles was also scanned to identify relevant literature.

2.1. Inclusion Criteria & Selection

The generalised selection criteria for article consideration of inclusion in the review were as follows: must be published in a peer-reviewed scientific journal; participants must be participating in field and/or court sports from a recreational level and above; written in English and/or have an English translated version. Specific selection criteria for inclusion in this review required studies to have sled-training-specific factors and a strong focus on expanding current sled tow literature and therefore, utilisation of a sled and the necessary sled towing equipment; needed to be either acute or longitudinal sled tow studies; sled tow loads needed to be specified; kinetic and/or kinematic sprint variables measured needed to be included and reported; measurement technologies used need to be reported. 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

3.1. Article Characteristics

A total of 114 articles were identified after database searches, 70 articles remained after the removal of duplicate articles (Figure 1.). 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.

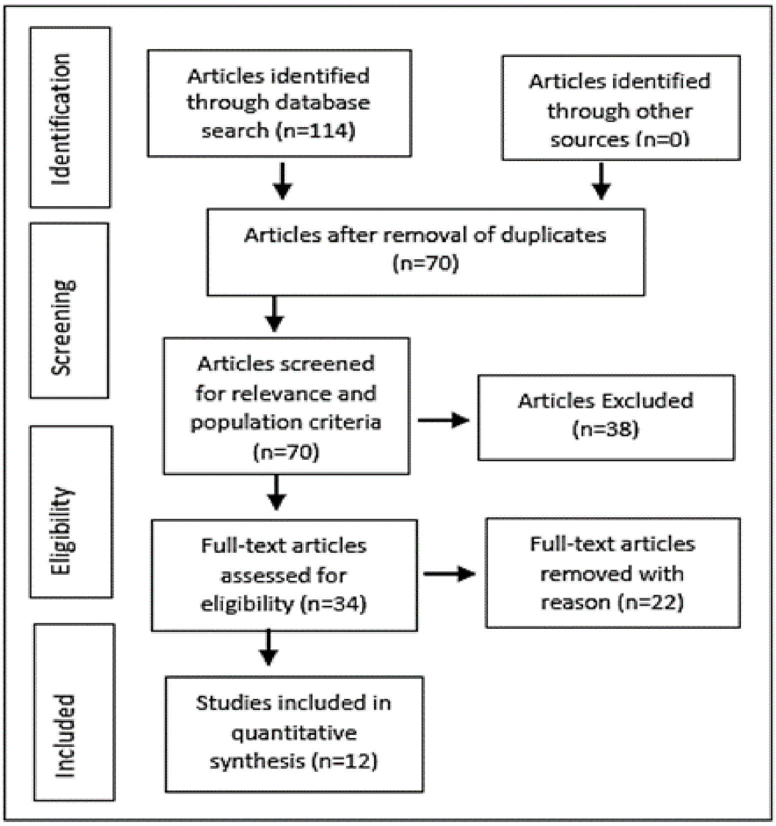

Figure 1: Diagram of study selection for review.

3.2. Participant Characteristics

From the literature that reported the sex of the participants, an obvious sex bias is present with eight of the articles reviewed using only male participants for testing (Cahill, Oliver et al., 2019; Cochrane & Monaghan, 2018; Kawamori et al., 2014; Morin et al., 2017; Murray et al., 2005; Tierney et al., 2019; West et al., 2013; Zabaloy et al., 2020), with the remaining articles using either both males and females (Cottle et al., 2014; Cross, Lahti et al., 2018) or only females (Petrakos et al., 2019). The age of male participants varied from 15.1 to 31.9 y with male youth participants reporting peak height velocity to take maturation into consideration of 1.80 ± 0.80 y (Cahill, Oliver et al., 2019). Female participants ages fell between 18.5 and 27.1 ± 2.30 y, however, due to age averages being combined with males, a maximum age is not able to be determined. It is important within sled tow research for weight to be reported as this has an influential effect on the outcome variables used in sled towing, however, on occasion, this information has been omitted (Cochrane & Monaghan, 2018; Cross, Lahti et al., 2018). Weight of male participants ranged between 64.2 kg to 114.4 kg. A single article reported female weight on its own being 64.8 ± 8.70 kg. All articles reported mean height of participants, however, the two articles that used both male and female participants used combined mean height rather than male mean height and female mean height (Cottle et al., 2014; Cross, Lahti et al., 2018). 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 (Petrakos et al., 2019). The skill level of the participants varies across the literature. Three studies testing recreational/amateur level athletes (Cahill, Oliver et al., 2019, Cross, Brughelli et al., 2017; Morin et al., 2017), four studies testing regional/semi-elite level athletes (Cochrane & Monaghan, 2018; Cottle et al., 2014; Kawamori et al., 2014; Zabaloy et al., 2020), three studies testing national/elite level athletes (Cross, Lahti et al., 2018; Tierney et al., 2019; West et al., 2013), and a further two studies testing a mixed level range of athletes (Murray et al., 2005; Petrakos et al., 2019). This is of importance as it provides a range of testing results, and therefore, a deeper understanding of how sled tow sprinting may vary amongst the different populations.

4. Measurement Systems

4.1. Radar Technology

Radar technologies are often used to assess on field linear sprinting with immediate sprint performance measures such as displacement, acceleration, maximal theoretical velocity (V0), maximal theoretical power (P0), and F0, making them an easy measurement device to use during sled tow sprints

(Simperingham et al., 2016; Simperingham et al., 2019). These measures provide necessary information to formulate a force-power-velocity (F-P-V) profile for individual athletes (Simperingham et al., 2016). Five of the studies utilised a radar device to measure sprint performance during sled tow sprints (Cahill, Oliver et al., 2019; Cross, Brughelli et al., 2017; Cross, Lahti et al., 2018; Morin et al., 2017; Zabaloy et al., 2020). 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) (Simperingham et al., 2016; Simperingham et al., 2019). Radar devices work off a Doppler principle and therefore are best utilised for linear accelerations/decelerations (Simperingham et al., 2016) 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 literature (Cahill, Oliver et al., 2019; Cross, Brughelli et al., 2017, Cross, Lahti et al., 2018; Morin et al., 2017; Zabaloy et al., 2020).

In field-based and team-sport athletes, validity of radar devices across 34 studies has generally been considered acceptable across populations (r = 0.87-0.99, absolute bias of 3-7%) when compared to force plates and photoelectric cells (Simperingham et al., 2016). While a review on the reliability measurements of sprint performance across 2-100m using radar technology has been reported for track and team sport athletes (Simperingham et al., 2016), only one study has reported that radar technology is reliable and valid for use in team sports (Cross, Brughelli et al., 2017). Though, this singular study did not provide specific statistical values (Cross, Brughelli et al., 2017). This is problematic as it provides limited certainty that radar technology is valid and reliable for different team sports when using radar to measure resisted sprint performance across a range of distances. Nevertheless, radar technologies are shown to have acceptable intra-day reliability ($CV \leq 9.5\%$, bias/systematic error $\leq 4.1\%$, $ICC \geq 0.84\%$) and a minimum of moderate inter-day reliability (bias/systematic error $\leq 6\%$, $ICC \geq 0.72$) in athletes across multiple sporting domains for distances up to 100m (Debaere et al., 2013; Ferro et al., 2012; Simperingham et al., 2016; Simperingham et al., 2019). 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, F-V slope, and relative F-V slope ($CV \leq 10\%$ & $ICC \geq 0.75$), while 2-10m split times are considered moderately reliable for relative F0, and relative Pmax) (Simperingham et al., 2019). This is thought to be due to the introduction of and increases of angle error (15o angle error = 3.4% recorded speed error) (Simperingham et al., 2016; Simperingham et al., 2019). Radar technology limitations exist across short distances of 0-5m, particularly from a standing start (Simperingham et al., 2016). This is thought to be due to postural changes, and therefore restricting valid and reliable information surrounding first step quickness when utilising radar technologies (Simperingham et al., 2016; Simperingham et al., 2019).

Radar technology may be considered 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 (Simperingham et al., 2016; Simperingham et al., 2019). However, coaches should be cautious when interpreting data from the first few steps due to potential increases in error. As coaches of rugby forwards specifically and court sports require force dominant acceleration from the early acceleration sprint phase for sprint performance enhancement, the inability to accurately measure the first few steps of a sprint is concerning within these sports (Ferro et al., 2012; Simperingham et al., 2016; Simperingham et al., 2019).

4.2. Laser/Timing Light Technology

Timing lights are considered to be ‘gold standard’ for sprint timing, acceleration, and speed assessment, with accuracies/samples of up to 0.01 sec (0.03 sec for 2-10m), therefore, it is seen amongst the literature to be an appropriate assessment tool for sled tow research (Cronin & Templeton, 2008; Earp & Newton, 2012; Murray et al., 2005). 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 (Cronin & Templeton, 2008; Earp & Newton, 2012). Timing systems can use single, dual, or triple photocells; the more photocells are present, the less likely error and bias is to be introduced, and the higher the cost of the equipment (Cronin & Templeton, 2008).

Five studies reviewed had 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) (Kawamori et al., 2014; Murray et al., 2005; Petrakos et al., 2019; West et al., 2013; Zabaloy et al., 2020). Of these studies, one reported reliability for single beam (ICC = 0.87-0.96, CV = 1.2% [0-20m] and 1.4% [20-40m]) (Petrakos et al., 2019). As previously mentioned, this singular study reporting of reliability is of concern as it does not provide reassurance amongst literature of the reliability of technology when assessing field and court sports specifically.

The most common variables measured were Vmax, Vdec, and sprint time (Kawamori et al., 2014; Murray et al., 2005; Petrakos et al., 2019; West et al., 2013; Zabaloy et al., 2020). 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. (2015), 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 stop watches (Earp & Newton, 2012; Haugen et al., 2014). 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

(Altmann et al., 2017; Altmann et al., 2018; Bond et al., 2016; Haugen et al., 2014).

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 (Altmann et al., 2017; Bond et al., 2016). 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) (Cronin & Templeton, 2008). 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 (Haugen et al., 2014).

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, further supporting the notion that single-beam timing lights are not suitable for sprints < 20m (Haugen et al., 2014). The absolute time difference of ± 0.06 sec is acknowledged as being three-times the value of the smallest worthwhile performance enhancement in team sports (0.2 of between-participant SD), further highlighting the accuracy differences between single and dual-beam timing systems (Haugen et al., 2014). However, it should be noted that dual-beam systems are not always available primarily due to the higher cost of the equipment (Earp & Newton, 2012). This is concerning for field and court sports as it places teams in a position of prioritising cost/availability of equipment over the accuracy of assessment results. Further to this, 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), preventing force dominant acceleration athletes from accessing accurate measures related to first step sprint acceleration (Cronin & Templeton, 2008; Haugen et al., 2014; Simperingham et al., 2019).

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 (Altmann et al., 2018; Bond et al., 2016; Earp & Newton, 2012). However, single-beam timing systems are not recommended for strength and conditioning coaches wanting highly accurate and reliable sprint times or in research/scientific settings (Altmann et al., 2017; Bond et al., 2016; Haugen et al., 2014).

4.3. Force Plates

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) (Exell et al., 2012; Loturco et al., 2018). Two studies utilised force plates to assess sprint performance using sled tow, however, neither study reported reliability or validity statistics (Cottle et al., 2014; Kawamori et al., 2014). Kawamori, et al. (2014), 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, 0.9m long, equipped with piezoelectric sensors [KI 9067; Kistler, Winterthur, Switzerland]). The requirement of a 23.1m extended sled tow tether (original tether = 3.9m) 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) (Kawamori et al., 2014).

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 (Exell et al., 2012). 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 gate (Challis, 2001; Exell et al., 2012; Samozino et al., 2015).

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 (Cross et al., 2017; Rabita et al., 2015; Samozino et al., 2015). 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 (Kawamori et al., 2014). Furthermore, most force-plate research has been conducted in a laboratory setting limiting the environmental errors and training specificity otherwise seen in within-field testing (Loturco et al., 2018).

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 (Loturco et al., 2018). 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 (Loturco et al., 2018). 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 (Loturco et al., 2018).

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 ($p \leq 0.001$; 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% (Peterson Silveira et al. 2017). 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 (Peterson Silveira et al., 2017).

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) (Kawamori et al., 2014). Braking and propulsive phases can also be determined by the positive and negative horizontal GRF (Kawamori et al., 2014). 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-V-P output as a result of training (Loturco et al., 2018).

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 (Cross et al., 2017; Samozino et al., 2015). Furthermore, force plate use in sled tow research and in the field is also limited by the inability to directly drag a sled over the plates as this risks damaging the plates (Kawamori et al., 2014). This limitation directly impacts the practicality of strength and conditioning coaches being able to use force plates for on-field sport-specific assessment, resulting in most field and court sports utilising other sled tow sprint assessment technologies. However, for coaches that are able to access and assess their athletes using force plates, caution should be exercised with interpreting results when using a limited number of force plates as there may be increased error in results due to athletes targeting the force plate.

4.4. Global Positioning Systems (GPS)

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 (Lacome et al., 2019; Varley et al., 2017). GPS is able to measure the distance travelled by an athlete using their positional differentiation from changes in device location using satellite signals (Varley et al., 2017). 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 (Haugen & Buchheit, 2016; Lacome et al., 2019; Roe et al., 2017).

From the literature reviewed, one study utilised GPS technology to assess sled tow sprinting (Tierney et al., 2019). No reliability or validity statistical values were reported. Tierney et al. (2019), utilised GPS micro-sensor technology units (StatSports Group Limited, Co.Down, Northern Ireland), collecting 10 Hz GPS data (augmented to 18 Hz), accelerometer data at 600 Hz, magnetometer data at 10 Hz, and gyroscope data at 400 Hz in their study of using momentum as a load prescription method similar to %Vdec to assess Vmax over a resisted 40m sprint. 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) (Roe et al., 2017). 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 (Haugen & Buchheit, 2016; Johnston et al., 2012; Varley et al., 2012). 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 (Haugen & Buchheit, 2016; Johnston et al., 2012). Therefore, more research needs to be undertaken to determine the validity and reliability for GPS during sled tow sprints, particularly as future developments occur with GPS technologies (Haugen & Buchheit, 2016).

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. This ultimately rules out the use of GPS in court sports, however, GPS technology use in field-sports is dramatically increasing because of its ability to provide real-time and in-game feedback to coaches (Haugen & Buchheit, 2016; Roe et al., 2017; Tierney et al., 2019). Coaches should take into consideration the Hz used and the environment (outdoors) when planning to utilise GPS technology.

5. Methodologies

5.1. Evaluation Protocols

Regarding testing standardisation and testing protocols used in the reviewed literature, the information reported and observed varied amongst the research. The majority of articles clearly defined, the use of a standardised warm-up prior to testing, if familiarisation sprints were undertaken and/or if participants were already familiarised with sled tow testing, reported the weight of the sled used, defined the rest periods prior to testing and between sprints, and all articles reported the use of a baseline unresisted sprint followed by multiple trials (Cahill, Oliver et al., 2019; Cochrane & Monaghan, 2018; Cottle et al., 2014; Cross, Brughelli et al., 2017; Cross, Lahti et al., 2018; Kawamori et al., 2014; Morin et al., 2017; Murray et al., 2005; Petrakos et al., 2019; Tierney et al., 2019; West et al., 2013; Zabaloy et al., 2020). 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

Table 1: Results of acute and longitudinal studies evaluating sled tow load-velocity.

Study	Participants	Measurement Technology	Evaluation Protocol	Load	Variables	Results
Cochrane & Monaghan, 2018	N=12, Male Age: 20.4 ± 1.2 years Height: 1.83 ± 0.72m 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 20m	Initial load of 75% and 115% BM, 35% and 55% Vdec	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, Oliver et al. 2019	N=70, Male Age: 16.7 ± 0.9 years Height: 1.77 ± 0.69m Weight: 75.6 ± 10.9kg 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-participant 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. 2019	N=13, Male Age: 25 ± 3 years Height: 1.86 ± 0.06m Weight: 103.9 ± 10.7kg Rugby Union	Micro-sensor technology units (StatSports Group Limited, Co. Down, Northern Ireland). 10 Hz GPS data (augmented to 18 Hz), accelerometer data at a rate of 600 Hz, magnetometer data at a rate of 10 Hz, and gyroscope data at a rate of 400 Hz.	8 weeks training phase of resisted sled sprint training sessions. Data collected as part of the participant's 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. 2020	N=20, Male Age: 22.5 ± 5.3 years Height: 1.80 ± 0.05m Weight: 80.2 ± 15.2kg 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 47 Hz and 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 350 Hz.	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, Vloss, 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. 2014	N=10, Male Age: 27.9 ± 1.9 Height: 1.76 ± 0.06m Weight: 80.2 ± 9.6kg 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	Ground Reaction Force, Contact time, Toe Off, Foot Strike, Braking, 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, Brughelli et al. 2017	N=12, (Sex not clarified) Age: 27 ± 4 years Height: 1.76 ± 0.08m Weight: 82.5 ± 10.47kg 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 46.9 Hz. 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. 2019	N=17, Female Age: 20.5 ± 2.0 years Height: 1.68 ± 0.65m Weight: 64.8 ± 8.7 kg Mixed field sports (field hockey, soccer, Gaelic football)	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. 2014	N=17, n=10 Male, n=7 Female Age: 20.9 ± 1.1 years Height: 1.7 ± 0.1m Weight: 62.2 ± 22.1kg Field & Court sports	AMTI BP400600 force plates (AMTI Watertown, MA, USA) set at 2400 Hz. 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. 2005	N=33, Male Age: 21.1 ± 1.8 years Height: 1.82 ± 0.1m Weight: 83.6 ± 13.1kg 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. 2017	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 ± 0.08m, control- 1.75 ± 0.08m Weight: experimental- 74.5 ± 5.3kg, control- 70.7 ± 6.5kg. 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 (i.e., 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. 2013	N=20, Male (Sled group, or traditional group) Age: SLED-26.8 ± 3.0 years, TRAD-25.1 ± 3.2 years Height: SLED-1.86 ± 0.80m, TRAD- 1.85 ± 0.70m Weight: SLED- 90.2 ± 10.3kg, TRAD- 90.9 ± 10.6kg Rugby Union	Electronic timing gates (Brower TC-System; Brower Timing Systems, Draper, UT, USA), set up at the start line and then 10 and 30m.	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, Lahti et al. 2018	N=15 (Soccer [S]), Male, N=21 (Rugby Union [R]), n=9 male, n=12 female Age: 27.1 ± 4.8 years(S), 27.1 ± 2.3 years (R) Height: 1.76 ± 0.36m (S), 1.75 ± 0.97m (R) Participants 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 46.9 Hz. Rugby- 1080 Sprint, (2000 RPM OMRON G5 Series Motor, OMORON Corporation, Kyoto, Japan.), collecting velocity-time data at a rate of 333-Hz.	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.

Note: ** Longitudinal studies

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, however, it should be noted that this is not necessarily reflective of performance settings in team sports (Haugen & Buchheit, 2016). 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 (Duthie et al., 2006; Haugen & Buchheit, 2016). It was common across the literature reviewed for researchers to undertake standardisation protocols to minimise the influence of internal and external factors on results.

Most of the articles reviewed reported the type of harness used to attach the sled being either a shoulder harness (Cochrane & Monaghan, 2018; Cross, Brughelli et al., 2017; Cross, Lahti et al., 2018; Kawamori et al., 2014; Petrakos et al., 2019) or waist harness (Cahill, Oliver et al., 2019; Cottle et al., 2014; Morin et al., 2017; Murray et al., 2005; Zabaloy et al., 2020), as well as the length of the tether which most commonly varied from 3.00-5.00m, with the shortest at 1.60m (Cochrane & Monaghan, 2018) and the longest at 23.1m (Kawamori et al., 2014). 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%) (Bentley et al., 2016; Cahill, Cronin et al., 2019). 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 (Bentley et al., 2016; Cahill, Cronin et al., 2019). When the harness is attached at the shoulders, there is a greater influence on knee and trunk joint kinematics compared to the waist attachment ($p \leq 0.05$) (Bentley et al., 2016). 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 (Bentley et al., 2016). However, this study only utilised loads of 10%Vdec over 6m, a distance known to have high variability (Bentley et al., 2016; Cahill, Cronin et al., 2019). 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 (Cross, Tinwala et al., 2016; Linthorne & Cooper, 2013). 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 (Cross, Tinwala et al., 2016). 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 ($\mu = 0.21\text{-}0.58$) (Linthorne & Cooper, 2013). 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 (Linthorne & Cooper, 2013). This result conflicts previous work by Andre et al. (2014), who found changes in coefficients of friction as load increased across all surfaces (Andre et al., 2013; Cross, Tinwala et al., 2016). 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 (Petrakos et al. 2019).

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 (Andre et al., 2013; Bentley et al., 2016; Cahill, Cronin et al., 2019; Cross, Tinwala et al., 2016; Duthie et al., 2006; Haugen & Buchheit, 2016; Linthorne & Cooper, 2013). 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 dependant on which method was used. The research reviewed used loads varying from 0-120% BM (Cochrane & Monaghan, 2018; Cottle et al., 2014; Cross, Brughelli et al., 2017; Cross, Lahti et al., 2018; Kawamori et al., 2014; Morin et al., 2017; Murray et al., 2005; Petrakos et al., 2019; West et al., 2013; Zabaloy et al., 2020), 10-75% Vdec (Cahill, Oliver et al. 2019; Cochrane & Monaghan, 2018), and 30-75kg absolute weight (Petrakos et al., 2019; Tierney et al., 2019), with two studies utilising a mixed methods approach to loading (Cochrane & Monaghan, 2018; Petrakos et al., 2019). 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 (Cahill, Cronin et al., 2019; Cahill, Oliver et al., 2019). 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 (Cahill, Cronin et al., 2019; Cahill, Oliver et al., 2019; Kawamori et al., 2014).

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 (Cahill, Cronin et al., 2019). Vdec is based off 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, dependant 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 (Cahill, Cronin et al., 2019; Cross, Brughelli et al., 2017; Kawamori et al., 2014). However, a recent systematic review on resisted sprint training for sprint performance by Petrakos et al. (2016), 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 (Petrakos et al., 2016; Petrakos et al., 2019). The review (Petrakos et al., 2016) 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 (Petrakos et al., 2016; Petrakos et al., 2019). Therefore, the external validity of this loading method has been brought into question due to the inability to directly compare findings across the literature (Petrakos et al., 2016; Petrakos et al., 2019).

Recently, research has branched into other possible methods of load prescription. Petrakos et al. (2019) explored the traditional 1-repetition max (1RM) load prescription method in order to take into account athletes' power-BM ratio. Rather than using Vdec, an athlete would otherwise be prescribed a %1RM dependant on the phase of the sprint, and thus strength capability, being targeted (i.e., speed-strength, power, strength-speed) (Petrakos et al., 2019). 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) measured by infrared single-beam timing lights (Fusion Sport, Queensland, Australia) (Petrakos et al., 2019). Petrakos et al. (2019), study also sought to identify reliability correlations for MRSL tests using Pearson's r values. Moderate (0.3-0.5) and large (0.5-0.7) 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 (Petrakos et al., 2019). 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 (Petrakos et al., 2019). 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 (Petrakos et al., 2019). 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 (Petrakos et al., 2019). 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 (Petrakos et al., 2019).

Another recently investigated method of loading includes the use of peak momentum to optimise acceleration performance (Tierney et al. 2019). This method is based off of the principle that momentum targets the different variables that improve sprint acceleration while taking into account an athletes BM, current inter-individual differences in sprint performance, and adversely to %BM and %Vdec can be compared across various distances (Tierney et al., 2019). 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 which 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 (Tierney et al., 2019). Therefore, more research is needed to confirm this theory, quantify momentum at various distances, and determine reliability and validity (Tierney et al., 2019).

The ongoing discussions and exploration of alternative loading methods to determine which method is best suited for individualised testing and training suggests 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. Overall the research is promising for field-sport practitioners as it allows for freedom of choice between methods, depending upon resources available, provided appropriate controls are in place.

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 (Cottle et al. 2014, Cross, Lahti et al. 2018, Kawamori et al. 2014, Morin et al. 2017, & Murray et al. 2005).

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 (Murray et al., 2005). This is in line with Kawamori et al. (2014), who found sled towing at 30%BM resulted in significant increases in ground contact time and decreases in stride length ($P = <0.05$) when compared to sprinting unresisted and with 10%BM (Elmontassar et al., 2018; Kawamori et al., 2014). However, stride frequency historically has been reported to decline non-linearly, with Murray et al. (2005) reporting no significant change in mean stride frequency as load increased, suggesting that changes in stride frequency may vary between athletes (Letzelter et al., 1995; Murray et al., 2005). 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 (Murray et al., 2005). 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 (Murray et al., 2005; Petrakos et al., 2016).

Research into the long-term effects of sled tow training appears to be relatively limited. Alcaraz et al. (2014), investigated the kinematic adaptations of a four-week sled tow training programme at 7.5%Vdec. The study found performance enhancements in the acceleration phase of sprint as a result of increased stride length with no effect on other kinematics (Alcaraz et al., 2014). However, there was 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 (Alcaraz et al., 2014). 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 (Alcaraz et al., 2014). 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 (Alcaraz et al., 2014; Petrakos et al., 2016).

A systematic review looking into resisted sled sprint testing for sprint performance improvement by Petrakos et al. (2016), has highlighted that there is variability 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. 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 (Petrakos et al., 2016). 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 (Cottle et al., 2014). 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 (Cottle et al., 2014; Kawamori et al., 2014). These findings suggest that sled tow loads of ≤ 10%BM had minimal effects on GRF (Cottle et al., 2014; Kawamori et al., 2014). Moreover, sled loads of ≤ 10%BM may preserve sprint kinematics (Kawamori et al., 2014). 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 (Clark et al., 2010; Cottle et al., 2014; Maulder et al., 2008). These acute results suggest that sled towing at loads above 20%BM are sufficient to overload sprint kinetics, primarily horizontal GRF's (Cottle et al., 2014; Kawamori et al., 2014). 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 (Morin et al., 2017).

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 (West et al., 2013). 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 (West et al., 2013). 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 (West et al., 2013). 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 (Cahill, Cronin et al., 2019).

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 methodology of 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 (Cahill, Cronin et al., 2019). The L-V relationship is characterised by a decrease in velocity as the load increases (linearity- $r > 0.95$) (Cahill, Oliver et al., 2019; Cross, Lahti et al., 2018). The L-V relationship is expressed as a parabolic power relationship when towing a sled (Cahill, Oliver et al., 2019). Cahill, Oliver et al. (2019), confirmed the linear L-V relationship to be reliable (CV = 3.1%) at Vdec of 10, 25, 50, and 75%. 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%) (Cahill, Oliver et al., 2019). Understanding the L-V relationship and how it is expressed during sled towing, has enabled coaches to prescribe appropriate loads for targeted training stimuli (Cahill, Oliver et al., 2019). 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 (Cross, Brughelli et al., 2017). The F-P-V relationship presents the neuro-muscular system's highest capacity to produce maximal force in the absence of velocity (F0), and the maximal velocity produced in the absence of force (V0) (Cahill, Oliver et al., 2019; Cross, Brughelli et al., 2017; Cross, Lahti et al., 2018). When the optimal capacities of force and velocity are combined, it is expressed as Pmax (Cross, Lahti et al., 2018). Often, these F-P-V relationships are profiled and used to identify if an athlete is force or velocity dominant and are used to advise load prescription dependent on which side needs improvement to enhance sprint or sport specific performance (Cochrane & Monaghan, 2018; Morin et al., 2017). 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 (Cross et al., 2017). Cross, Brughelli et al. (2017), investigated the ability for F-P-V relationships to be profiled from multiple sled tow sprints, and if loading could then be optimized to enhance power based off of the profiles. 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 (Cross, Brughelli et al., 2017). However, multiple sled tow sprints are required, and therefore, are not necessarily time efficient or practical (Cross, Brughelli et al., 2017). 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 (Cross, Brughelli et al., 2017).

Following a similar concept of identifying optimal load prescriptions, Tierney et al. (2019), sought to identify and utilize peak momentum to prescribe sled tow loads. 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 (Tierney et al. 2019). In regard 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. (2017), 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. 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) (Morin et al. 2017). 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) (Cochrane & Monaghan, 2018). 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 (Cochrane & Monaghan, 2018; Cross, Brughelli et al., 2017; Cross, Lahti et al., 2018; Morin et al., 2017).

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 assessed in literature in the context of field and court sport athletes. The literature highlights expansions of research including what loads are best to optimize different sprint performance aspects, 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 assessment. This review has also identified a number of limitations, and therefore, further research within resisted sled tow literature is required to 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 utilized, and when targeting maximal velocity, lighter sled loads should be utilized. The current technologies are able to accurately measure various F-V related sled tow variables from mid acceleration onwards (>10m). However, there are limited technology and methods available that can accurately assess kinetics during the early acceleration phase (<5m) and easily provide direct measures of kinetics and kinematics beyond 5m. This provides scope 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 no conflict of interests.

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