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# The effect of high intensity, short duration trampolining on human physiology across an 8-week intervention

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ABSTRACT

*The aim of this study was to investigate whether a high intensity, short duration protocol on a trampoline would significantly alter physiological markers across an 8-week intervention. A controlled trial design was used. Twenty-three healthy adults were recruited for the study. The intervention group completed 100 bounces on a trampoline, at the maximum possible intensity, 4 times per week for 8 weeks. The control group maintained their current level of exercise across the 8 weeks. Body fat, muscle mass, blood pressure, resting heart rate, blood oxygenation, blood pressure, total blood cholesterol (fasted),* $\dot{V}O_2max$ *and vertical jump were assessed at Week 0,4 and 8 for both groups. A one way repeated measures MANOVA was used for both the intervention and control group. A difference was found between the means of the variables for the intervention group, but not for the control group. Analysis was then continued, for the intervention group, to discern where the change had occurred. A series of one way repeated measures ANOVAs found a significant change had occurred for blood cholesterol, relative* $\dot{V}O_2$*, vertical jump, total bounce height, time to completion and caloric expenditure. The results of this study indicate that using a high intensity, short duration protocol on a trampoline may improve physiological markers with as little as eight minutes of exercise per week. Therefore, this could provide a novel and time efficient method of exercise.*

## 1. Introduction

Engaging in regular exercise causes adaptions to many physiological markers which in turn may provide various health benefits including; increased muscle mass (Rogers & Evans, 1993), increased bone density (Marques et al., 2012), improved cardiovascular function (Berthouze et al., 1995), mental health benefits (Lawlor & Hopker, 2001) and a decreased mortality risk (Nocon et al., 2008). Despite this, lack of regular exercise is the fourth greatest risk factor for non-communicable diseases, which is estimated to cause 3.2-5 million deaths per year (McIntyre, 2015). One of the most common barriers to engaging in regular exercise is a lack of time (Schutzer & Graves, 2004). The current guidelines for physical activity recommend either 2.5 hours of moderate or 1.25 hours of vigorous intensity exercise per week (McIntyre, 2015). For a person with limited free time this may be an unrealistic goal.

Low availability of free time is commonly listed as a major contributing factor to lack of participation in exercise (Greaney et al., 2009). Therefore, if the duration of exercise can be reduced, this may make participating in regular exercise more attractive. In recent years the popularity of high intensity interval training (HIIT) has increased dramatically. The premise behind HIIT training is to use a high work intensity across multiple, short duration bouts to reduce exercise time. Meta-analyses investigating HIIT vs steady state exercise found either superior or matched improvements to cardiovascular function (Ramos et al., 2015) and body composition (Wewege et al., 2017), despite steady state exercise being performed for significantly longer periods of time. This difference in required time makes HIIT an attractive exercise modality to those with limited time availability.

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Jumping on a non-compliant surface as an exercise regime (also known as plyometrics) has been investigated extensively. Plyometrics have been shown to provide significant benefit to; leg muscular power output (de Villarreal et al., 2009; Stojanović et al., 2017) and bone density (Zhao et al., 2014). Comparisons between the training results of jumping on a compliant surface (such as a trampoline) and a non-compliant surface (such as the ground) may not be appropriate. This is because it has been shown that the jumping action significantly differs between a compliant and non-compliant surface (Crowther et al., 2007). Therefore, conclusions from studies conducted on non-compliant surfaces may not be applicable to trampolining.

Mini-trampolines (also known as rebounders) are the most popular, compliant-surface, modality used in a research setting. Exercise using rebounders has been shown to improve; stability (Arabatzi, 2018), vertical jump (Şahin et al., 2016), anthropometric measures (Cugusi et al., 2016), cardiovascular function (Şahin et al., 2016) and insulin resistance (Nuhu & Maharaj, 2017). At the surface level, the bouncing action of rebounders and trampolines may appear similar, but there are some fundamental differences. On a rebounder, the bouncing action is often focused on a downward push into the mat, which limits the upwards propulsion (McGlone et al., 2002). Whereas, the bouncing action on a trampoline is solely focused on upwards propulsion. The bouncing action on a rebounder can then be further characterised as either a "bounce" or a "jog". With the different characterisations producing significantly different physiological responses (Gerberich et al., 1990). How these differences between the bouncing action on a trampoline and rebounder affects the results of a training regime haven't been investigated at this time. Therefore, the conclusions from studies conducted on rebounders may, also, not be applicable to trampolining.

Research directly investigating exercise on trampolines has shown significant benefit to; anthropometric measures, jump height, balance and leg power (Aalizadeh et al., 2016). Some papers have also investigated rate of energy expenditure while bouncing on a trampoline (Alexander et al., 2020; Clement et al., 2020; Draper et al., 2020), which required measurement of oxygen consumption during exercise. No papers, at this point, have directly investigated the efficacy of using a trampoline to improve cardiovascular fitness.

For a protocol to be considered HIIT, multiple intervals must be used. Due to the appeal of low time commitment, a single, max effort, protocol was devised. This experiment uses a single, high intensity, short duration (HISD) protocol. To the best of the author's knowledge a HISD protocol hasn't been used before. Therefore, the aim of this study was to investigate whether HISD exercise, on a trampoline, would significantly improve physiological markers across an 8-week intervention.

## 2. Methods

### *2.1. Participants*

The study was completed in three separate blocks from September 2018-November 2018, February 2019-June 2019 and June 2020-August 2020. Twenty-five participants were recruited for the intervention group (8 were removed due to non-adherence, two were removed due to injury/sickness not related to the study, one was removed due to injury related to the study). Ten participants were recruited for the control group (One was removed due to non-adherence).

The analysis group consisted of 23 healthy adults (8 Male, 15 Female) (14 intervention group, 9 control group). Participants ranged from 19-60 years of age, with a mean age of 29±12 years. Means of the anthropomorphic measures for males and females were respectively; height (180 ± 3cm) (164 ± 5cm), mass (93 ± 18kg) (71 ± 15kg) and BMI (29 ± 7) (27 ± 6). The participants had a range of prior trampolining experience, ranging from having no prior trampolining experience to having four years of experience competing in gymnastic trampolining. None of the participants had regularly bounced on a trampoline in the prior five years to beginning the study. Exclusion criteria were health risks that contraindicate exercise testing (American College of Sport Medicine, 2013), diseases that are associated with loss of balance, as well as the presence of infections, injuries or an existing drug treatment that could potentially limit physical performance. Participants who passed the screening were given detailed information about the study's aim and protocol and gave written consent before participation. This study was approved by the ethics committee of the University of Canterbury and was registered with the Australia, New Zealand Clinical Trials Registry (26/11/2019), registration number: ACTRN12619001646134. All procedures were performed in accordance with the relevant guidelines and regulations.

### *2.2. Procedure*

#### *2.2.1. Testing*

Participants were required to visit the University of Canterbury Physiology Laboratories at Week 0, Week 4 and Week 8 of the intervention. The full testing session took approximately an hour each visit. All testing sessions were completed in the morning and participants were instructed to fast prior to the session (no water or food since the previous evening).

Body mass was obtained using a bio-impedance scale (Inbody 230, Inbody, Seoul, Korea). Body-fat and muscle mass were obtained using the same machine by method of bioelectrical impedance analysis (Lukaski et al., 1985). Next, blood pressure was assessed using an automated blood pressure cuff (5200-103Z, Welch Allyn, New York, USA), which measured the participants resting heart rate, blood oxygenation and systolic/diastolic blood pressure. Total blood cholesterol (fasted) was then assessed using lancet blood sampling (BK6-10M, Benecheck, New Taipei City, Taiwan).

At this point the participants were encouraged to eat and drink if they desired. Next, each participant underwent a $\dot{V}O_2$max test using an athlete led protocol (Hamlin et al., 2012) using a breath by breath analyser (K5, COSMED, Rome, Italy) to assess $\dot{V}O_2$max. Following the $\dot{V}O_2$max, the participant was instructed to rest until they felt fully recovered (a 5-minute minimum was utilised). Finally, anaerobic power was assessed using vertical jump height (Yardstick, Swift Performance Equipment, NSW, Australia). The participant was instructed to stand beneath the yardstick, then to extend their arm up and swipe the highest marker they could reach without their heels coming off the floor.

This value was considered their reach. For each jump, their reach was subtracted from total jump height. For their jumps, no run up was allowed. Each participant was allowed three attempts. A one-minute rest was used between attempts. Their highest score was recorded.

Finally, the average amount of hours the participant spent exercising, weekly, outside of the intervention, was recorded. Participants were instructed to maintain their current level of exercise outside of the intervention and were excluded if the amount changed by more than an hour per week.

#### *2.2.2. Intervention*

For the duration of the 8 weeks, the intervention group were required to come into the laboratory 4 times per week to bounce on the designated trampoline (O77, Springfree, Christchurch, New Zealand). Participants were excluded if they completed less than an average of 4 sessions per week. Each session consisted of the participants first completing a 10-bounce warm-up at a self-directed, moderate intensity. The participant then completing a further 100 bounces at the maximum intensity (height) they were capable of. For each session; time to completion, total bounce height (the cumulative height of the 100 bounces) and caloric expenditure (during the 100 bounces) were recorded using the TGOMA software on the trampoline (TGOMA, Springfree, Christchurch, New Zealand).

The control group completed no bouncing sessions during the 8 weeks and were instructed to maintain their current level of exercise.

### *2.3. Statistical Analysis*

Statistical analysis was performed using SPSS Statistics for Windows (Version 25.0, IBM Corp, Armonk, NY, USA). Datasets were first assessed for normality using a Shapiro-Wilks test. All variables were found to follow a normal distribution, therefore multivariate normality was assumed. Two, separate, one way repeated measures MANOVAs were used to assess whether significant differences existed between the means, for each of the variables, for both the intervention and control group ($p \leq 0.05$). Significant difference was found between the variables for the intervention group, but not the control group. Due to finding no significant differences analysis was not continued for the control group.

For the intervention group, a series of repeated measures ANOVAs were used to identify the degree of significance between the time points for each of the variables. The data set for vertical jump failed Mauchly's Test of Sphericity ($p$ = 0.006), therefore a repeated measures ANOVA with a Greenhouse-Geisser correction was used for this dataset. Partial eta squared was used to interpret the effect size for all variables. Post hoc tests using the Bonferroni correction were then used to identify when these changes occurred for each of the variables.

Finally, independent samples t-tests were used to compare means, between the intervention and control group, for vertical jump and relative $\dot{V}O_2max$, for each of the time points. To investigate whether either group began with a significantly higher base fitness.

## 3. Results

Two, one way repeated measures MANOVAs were used to assess whether significant differences existed between the means for mass, muscle mass, fat mass, blood pressure, blood cholesterol, relative $\dot{V}O_2max$ and vertical jump for both the intervention and control group. A difference was found between time points for the intervention group ($F_{12,18}$= 2.767, $p$ = 0.038), but not for the control group ($F_{14,16}$= 0.654, $p$ = 0.794). Descriptive statistics for the control and intervention can be seen in Table 1.

A series of one-way repeated measures ANOVAs were then used to identify which of the measured variables had changed for the intervention group. A difference was found for blood cholesterol ($F_{2,26}$= 7.358, $p$ = 0.003, $\eta_p^2$ = 0.4), relative $\dot{V}O_2max$ ($F_{2,26}$= 4.185, $p$ = 0.027, $\eta_p^2$ = 0.2), vertical jump ($F_{1.267,16.468}$= 10.547, $p$ = 0.003, $\eta_p^2$ = 0.4), total bounce height ($F_{2,26}$= 4.956, $p$ = 0.015, $\eta_p^2$ = 0.3), time to completion ($F_{2,26}$= 20.779, $p$ < 0.0005, $\eta_p^2$ = 0.6) and caloric expenditure ($F_{2,26}$= 4.956, $p$ = 0.015, $\eta_p^2$ = 0.3).

Table 1: Means ± SD of the variables for the control and intervention groups.

| | Control Pre | Control Post | Intervention Pre | Intervention Post |
|---|---|---|---|---|
| Mass (kg) | 79 ± 18.2 | 79.4 ± 19.3 | 78.6 ± 20.0 | 78.6 ± 20.1 |
| Muscle Mass (kg) | 31 ± 7.6 | 31.6 ± 7.7 | 30.5 ± 8.0 | 30.5 ± 8.0 |
| Fat Mass (kg) | 24 ± 13.8 | 23.5 ± 12.7 | 24.1 ± 12.8 | 24.3 ± 12.7 |
| Systolic Blood Pressure (mmHg) | 123 ± 13 | 119 ± 10 | 119 ± 14 | 114 ± 14 |
| Diastolic Blood Pressure (mmHg) | 76 ± 9 | 74 ± 6 | 74 ± 7 | 73 ± 8 |
| Blood Cholesterol (mmol/L) | 4.5 ± 0.5 | 5.5 ± 1.5 | 5.0 ± 1.3 | 5.7 ± 1.7 |
| Relative $\dot{V}O_2$ (mL/min/kg) | 44 ± 8.5 | 40.8 ± 7.2 | 40.2 ± 8.4 | 42.6 ± 9.9 |
| Vertical Jump (cm) | 41 ± 9 | 43 ±10 | 32 ± 9 | 36 ± 9* |

*Note:* * indicate significant change occurred within the intervention group

Table 2: Means ± SD of the variables for the intervention group.

| | Week 0 | Week 4 | Week 8 |
|---|---|---|---|
| Mass (kg) | 78.6 ± 20.0 | 78.7 ± 20.9 | 78.6 ± 20.1 |
| Muscle Mass (kg) | 30.5 ± 8.0 | 30.2 ± 8.8 | 30.5 ± 8.0 |
| Fat Mass (kg) | 24.1 ± 12.8 | 25.1 ± 14.1 | 24.3 ± 12.7 |
| Systolic Blood Pressure (mmHg) | 119 ± 14 | 119± 15 | 114 ± 14 |
| Diastolic Blood Pressure (mmHg) | 74 ± 7 | 75 ± 9 | 73 ± 8 |
| Blood Cholesterol (mmol/L) | 5.0 ± 1.3 | 6.2 ± 1.4* | 5.7 ± 1.7 |
| Relative $\dot{V}O_2$ (mL/min/kg) | 40.2 ± 8.4 | 44.1 ± 7.4* | 42.6 ± 9.9 |
| Vertical Jump (cm) | 32 ± 9 | 34 ± 9 | 36 ± 9* |
| Total Jump Height (m) | 46 ± 20.7 | 61.6 ± 24.7* | 69 ± 25.7 |
| Time to completion (s) | 110 ± 9 | 116 ± 10* | 119 ± 11* |
| Caloric Expenditure (kcal) | 34 ± 27 | 45 ± 43* | 50 ± 48 |

*Note:* * indicates significant change occurred within the intervention group

Post hoc tests found that blood cholesterol increased Week 0-4 ($p = 0.001$). No change occurred Week 4-8 ($p = 0.403$). Overall, no change occurred Week 0-8 ($p = 0.255$).

Relative $\dot{V}O_2$max increased Week 0-4 ($p = 0.04$). No change occurred Week 4-8 ($p = 0.481$). Overall, no change occurred Week 0-8 ($p = 0.502$).

For vertical jump, no change occurred Week 0-4 ($p = 0.213$). An increase occurred Week 4-8 ($p = 0.002$). Overall, an increase occurred Week 0-8 ($p = 0.005$).

Total bounce height increased Week 0-4 ($p = 0.04$). No change occurred Week 4-8 ($p = 0.114$). Overall, an increase occurred Week 0-8 ($p = 0.04$).

For time to completion no change occurred Week 0-4 ($p = 0.035$). An increase occurred Week 4-8 ($p = 0.001$). Overall, an increase occurred Week 0-8 ($p = 0.035$).

Caloric expenditure increased Week 0-4 ($p = 0.04$). No change occurred Week 4-8 ($p = 0.114$). Overall, an increase occurred Week 0-8 ($p = 0.04$). Descriptive statistics for the variables of the intervention group can be seen in Table 2.

Finally, independent samples t-tests were used to compare the means for vertical jump and relative $\dot{V}O_2$max between the intervention and control group for each of the time points. This was to confirm that both the intervention and control group began with a similar baseline fitness. No differences were found for either variable for any of the time points ($p < 0.05$).

## 4. Discussion

The aim of the study was to investigate whether a HISD protocol on a trampoline would cause significant change to physiological markers of the participants. Omnibus tests indicated significant change had occurred for the intervention group, but not for the control group (see Table 1). Further analysis for the intervention group found that the change had occurred for blood cholesterol, relative $\dot{V}O_2$max, vertical jump, total bounce height, time to completion and caloric expenditure.

No significant change occurred for mass, muscle mass, fat mass or blood pressure for either group (see Table 1). This suggests that this intervention had little to no effect on these attributes, for the considered time frame, and therefore is likely not a viable modality for affecting change related to these markers.

The intervention group did see an increase to the total blood cholesterol Week 0-4. Exercise may affect blood cholesterol by increasing the concentration of high-density lipoprotein (HDL) (Tambalis et al., 2009). Increasing the concentration of HDL relative to low-density lipoprotein (LDL) is considered to be a positive change (Hooper et al., 2001). It is also well known that high total blood cholesterol is a risk factor for heart disease (Kannel et al., 1971). The measuring equipment used in this study was unable to discern between HDL and LDL concentration. Therefore, it cannot be concluded whether this change in total blood cholesterol was positive or negative. Future research, using more sensitive testing equipment, is necessary to ascertain the nature of this change.

This research found that relative $\dot{V}O_2$max increased Week 0-4, then no change occurred Week 4-8 for the intervention group. With overall, (Week 0-8) no change occurring. The authors' hypothesis for this phenomenon is that the participants tried significantly harder during the $\dot{V}O_2$max in the Week 0 and Week 4 testing days. This theory is supported by two different results. First, the control group (see Table 1) saw a negative change in their $\dot{V}O_2$max. The control groups Week 0 $\dot{V}O_2$max was 44 ± 8.5 which then decreased to 40.9 ± 9.4 in Week 4 and decreased again to 40.8 ± 7.2 in Week 8. Whereas, the intervention group improved from their Week 0 result. Second, manual inspection of the graphs of output of the $\dot{V}O_2$max tests, showed a distinct lack of plateauing of the gradient of the graph for five of the participants (3 intervention, 2 control). This indicates that these participants did not reach their $\dot{V}O_2$max during the final testing day (Week 8). The protocol used in this study was athlete-led. With the participant instructed to cease the test at the point where they felt they could no longer continue. Max effort cardiovascular tests are inherently difficult. Requiring pushing to a level of fatigue that most participants find unpleasant. It is likely that participants were unwilling to exert themselves as strongly in the latter testing days, therefore lowering their results. Pushing to extreme fatigue is likely to injure the participant. Further research should consider this phenomenon and be prepared to control for it.

These results indicate that cardiovascular fitness may be improved above the baseline level with a low exercise dosage on a trampoline. The current guidelines for physical activity recommend either 2.5 hours of moderate or 1.25 hours of vigorous exercise per week to maintain good health (McIntyre, 2015). The protocol used in this study equated to approximately 6-8 minutes of vigorous exercise per week. This means that just 10% of the recommended dosage caused an improvement to the participant's fitness. This indicates that a HISD protocol on a trampoline could be a relevant exercise modality for those with limited time availability for exercise. Further research with a larger sample size is necessary to further validate this finding.

A draw-back of traditional HIIT training is it requires an intensive warm-up protocol to allow maximum effort exertion, as high exertion from a resting state dramatically increases the chance of injury (Shellock & Prentice, 1985). Warm ups associated with HIIT are often similar in length to the exercise protocol (10 minutes warming up vs 16 minutes of HIIT) (Foster et al., 2015). Traditional warm up times for vigorous exercise can be anywhere from 5-30 minutes long (McGowan et al., 2015). For this study the protocol utilised a warm-up consisting of 10 bounces on the trampoline, at a moderate intensity, selected by the participant. This took approximately 10 seconds to complete and, therefore, did not add a significant amount of time to the protocol. This suggests that a HISD exercise protocol on a trampoline may be an even more time efficient exercise modality than traditional forms of HIIT. Of note is that one participant dropped out this study due to an injury sustained during the study, so further investigation is necessary to validate the use of such a short duration warm up.

The participant's vertical jump also improved significantly. Two papers were found investigating trampolining's effect on vertical jump. Both reported trampolining significantly improved vertical jump (Atilgan, 2013; Ross & Hudson, 1997). The authors hypothesised that the increased vertical jump was because of improvement to the participant's jumping technique, specifically to their co-ordination (the timing of the contraction of the participant's muscles during their jump). This study has found a similar result. This suggests that trampolining is a viable modality for improving the technique of a vertical jump. This may also lead to improvement in the user's vertical jump height.

Of note is that the participant's trampolining ability increased dramatically during the intervention. Improvement to trampolining ability can be measured by an increase to the participant's total bounce height. Improving total bounce height will also increase time spent in the air and caloric expenditure. The average Week 0 total bounce height was 46 meters which, by Week 8, increased to 69 meters. This meant the amount of work done during each session increased dramatically across the intervention. Exercise has a dose-response relationship (Iwasaki et al., 2003). This means that as work increases, the response to exercise increases proportionally. Across the intervention, the average total bounce height of the participants increased by 50%. Therefore, their work output became significantly higher towards the end of the intervention. This indicates that the participants experience a significant learning effect across the intervention. Such a dramatic improvement in ability is unlikely to occur during a study using more traditional exercise modalities (such as running or biking). This is because the participant is likely to have a higher previous experience level with the more common exercise modalities. By increasing the length of the intervention, the learning effect of a novel exercise will be minimized. Further research should consider using longer intervention lengths to mitigate how the learning effect affects outcomes on a trampoline.

## Conflict of Interest

The authors declare no conflict of interests.

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# Natural development of sprint speed in girls and boys: a narrative review

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ABSTRACT
*Sprinting is a fundamental motor skill in many sports. The ability to move rapidly over short distances can significantly impact the outcome of a game. The natural development of sprinting speed is similar in females and males during the first decade of life. However, due to changes in hormonal levels during puberty the development of kinetic and kinematic variables associated with sprinting may be affected in young females compared to their male counterparts. Previously researchers have investigated sprinting kinetics and kinematics in young males. However, there is a paucity of research on young females. Therefore, the purpose of this review is to highlight the biological differences between genders with regard to sprinting and the changes in kinetics and kinematics across maturation in young females.*

## 1. Introduction

Boys and girls tend to show similar sprinting speed during the first decade of life (Borms, 1986; Malina et al., 2004), with a period of accelerated change between 5 and 9 years of age (Borms, 1986; Viru et al., 1999). Speed increases in this age group with the development of the central nervous system and subsequent improvements in coordination (Borms, 1986; Viru et al., 1999). However, from the age of 12 years, increases in sprinting speed slow considerably in girls compared to boys (Whitall, 2003). This disparity is largely due to maturational changes in body size and composition (Beunen & Malina, 1988; Butterfield et al., 2004), driven largely by hormonal changes. Because sprinting is heavily influenced by the stretch-shortening cycle (SSC) (Radnor et al., 2018), the physiological determinants of the SSC, including muscle size, fibre composition, and connective tissue/tendon stiffness (Bell et al., 1980; Lazaridis et al., 2010; Lexell et al., 1992; McLellan et al., 2011; Tillin et al., 2013), are also important to consider. Therefore, this review will highlight the differences in body composition, muscle size, fibre composition, connective tissue stiffness, growth and maturation in boys and girls regarding sprinting performance. The review will then investigate two models proposed by previous researchers to optimise sprinting performance in boys and girls and, the changes in sprinting kinetics and kinematics across maturation in the youth population.

## 2. Body size and composition

Insulin-like growth factor 1 (IGF-1), an important growth hormone in children, peaks during early adolescence. This anabolic hormonal surge occurs at approximately 12-13 years in girls and 15-16 years in boys (Underwood & Van Wyk, 1985). The anabolic factors can influence the development of muscle tissue hence affecting muscle strength, speed, and power around puberty in girls (Viru et al., 1999). However, this period coincides with sexual maturation in girls, which results in an increase in adipose tissue compared to their male counterparts (Malina et al., 2004; Viru et al., 1999). This can particularly impact movements during which body mass is supported, for example, running and jumping activities (Viru et al., 1999). In contrast, the androgenic effects of testosterone during puberty increases lean muscle mass in boys, which can positively impact weight to power ratio (Malina et al., 2004). Therefore, the differences in the interaction between hormonal changes and sexual maturation may provide an advantage to boys over girls when it comes to sprinting.

The changes in body size occur as a natural response to growth during early adolescence phase in boys and girls. Peak weight

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velocity (PWV; the greatest rate of change in body mass) reaches 8.3kg/year in girls at about 12.5 years of age (Barnes, 1975). In boys, peak gains in weight are similar but experienced at a relatively later age (i.e., 14 years) (Barnes, 1975). Similarly, the maximum rate of linear growth, defined as PHV (Brown, Patel, & Darmawan, 2017), tends to occur at 12 years of age in females, approximately 6-12 months before the onset of puberty. During PHV, changes in height average 8 centimetres (cm) per year, with a range of 6-10.5 cm (Hoffman, 1997; Kreipe, 1994; Needleman, 2004). Boys reach PHV at approximately 14 years of age, with average gains in height ranging from 7-12 cm (Hoffman, 1997; Kreipe, 1994; Needleman, 2004).

Rapid increases in PHV and PWV can affect physical competencies, including sprinting (Malina et al., 2004). For example, previous research has shown a positive relationship between standing height and sprint speed in prepubertal boys, and leg length and sprint speed in post-pubertal boys (Meyers et al., 2017a). The positive association between height, leg length and sprint speed can be explained by the relationship between the distance the centre of mass travels after the foot hits the ground (i.e., contact length) and an increase in step length that occurs naturally as a result of growth (Lloyd et al., 2016b; Meyers et al., 2017a). In girls, Talukdar et al. (2021) reported that with every cm increase in leg length, maximal sprint decreased by 0.05 m/s in mid and post-PHV athletes.

Children also experience significant changes in body composition during puberty (Patel, Pratt, & Greydanus, 1998; Roemmich, & Rogol, 1995). For instance, both fat mass (FM) and fat-free mass (FFM) increase between 9 and 15 years of age in girls and boys (Malina et al., 2004). However, due to the development of secondary sex characteristics (e.g., wider hips, breast development), a consequence of increased growth hormone secretion, deposits of fat mass are significantly higher in girls with an average of 7.1kg compared to 3.1kg in boys (Malina et al., 2004). Moreover, proportionately more body fat is concentrated in the lower body of girls (Papai et al., 2012). The increase in body mass may inhibit force production in girls particularly during sprinting, as based on Newton's second law of motion, the greater the body mass the greater the acceleration required to displace the body. Rumpf et al. (2015) reported relative horizontal force and power to be the best predictors of maximal sprinting speed across maturation in young males ($R^2$ = 97-99%).

Body fat mass has also been shown to have a negative influence on sprint speed in youth athletes (Meyers et al., 2017a). For example, Meyers et al. (2017a) reported that body mass was negatively related to 30 sprint speed in both pre- and post-PHV boys ($r$ = -0.35 & -0.47; $p < 0.05$). More specifically, in pre-PHV boys, body mass had a negative influence on step frequency ($r$ = -0.48). In post-PHV boys, body mass negatively influenced step length ($p < 0.05$, $r$ = -0.54) (Meyers et al., 2017a). Therefore, it is important to assess changes in height, weight, and body composition, particularly during the time of puberty as it can affect sprinting performance in the youth population.

Higher fat deposition in girls, a result of increasing oestrogen levels (Malina et al., 2004), may also affect sprinting kinetics and kinematics (Beunen & Malina,1988; Butterfield, Lehnhard, Lee, & Coladarci, 2004; Malina et al., 2004). Nagahara et al. (2019) investigated change in sprinting performance in Japanese girls between the ages of 7.0 and 15.3 years. The findings showed that girls >12.7 years became slower every year (-0.09 m/s) compared to girls <12.7 years (0.24m/s). Furthermore, the older girls had a plateau in step length and a reduction in ground reaction forces (GRFs) compared to the younger girls (Nagahara et al., 2019). Due to an increase in fat mass as girls mature, relative force production and step length can be considerably reduced, negatively impacting sprinting performance. Apart from body size and composition, there are other physiological differences between the genders that can impact sprinting performance such as SSC, muscle size, fibre composition, and muscle tendon stiffness.

## 3. The stretch-shortening cycle

SSC is characterised by an eccentric 'stretching' action before subsequent rapid concentric action. Sprinting, jumping and throwing utilises the SSC (Lloyd et al., 2015). It has been reported that this action (eccentric stretch before concentric) is more useful in improving the performance of the final concentric phase compared to an isolated concentric action (Flanagan & Comyns, 2008; Nicol et al., 2006). For example, jump height was reported to increase by 1-5% when preceded by countermovement (pre-stretch action) in young males (Lloyd et al., 2009). Furthermore, SSC can be categorised into fast and slow action based on ground contact time. Ground contact time shorter than 250ms is generally classified as fast SSC and ground contact time above 250ms is considered slow SSC (Flanagan & Comyns, 2008; Turner & Jeffrey, 2010). Sprinting can be considered a fast SSC activity since the ground contact time is lower than 250ms. In mid and post-PHV female athletes, the ground contact time was reported to be 170m/s (0.17s) (Talukdar et al., 2021). The function of the SSC is determined by several physiological variables, including muscle size, fibre composition, and connective tissue/tendon stiffness which may vary between genders (Radnor et al., 2018).

## 4. Muscle size

It is believed that increases in muscle size can contribute to the improved capacity to produce force which leads to greater performance outcomes during SSC activities (Radnor et al., 2018). Muscle size increases with growth and biological maturation with the ability to produce higher force during both concentric and eccentric actions (Kubo et al., 2001; O'Brien et al., 2010a; O'Brien et al., 2010b). More specifically, in isolated concentric and eccentric muscle actions, muscle size has been associated with quadriceps and hamstrings concentric strength and hamstring eccentric strength (Morse et al., 2008). Greater concentric strength during SSC actions can contribute towards greater impulse and rate of force development hence providing superior performance during sprinting and jumping tasks (McLellan et al., 2011; Tillin et al., 2013). In addition, as muscles increase in size during growth, the higher forces during the eccentric phase of sprinting and jumping may result in increased storage of elastic energy (Komi, 2000). Therefore, increases in lean muscle mass and size in boys can be an advantage for SSC-based activities such as sprinting compared to their female counterparts.

## 5. Fibre type composition

In addition to muscle size, fibre type composition can also play an important role in sprinting (Bell et al., 1980). Type 2 muscle fibres help to improve the ability to rapidly produce force resulting in greater benefit from the SSC compared to type 1 fibres (Radnor et al., 2018). It is reported that type 1 fibres decrease from approximately 65% at age 5 years to 50% at age 20 years (Lexell et al., 1992). However, limited longitudinal data have reported that gender differences in fibre type can be evident as the adolescent transitions towards adulthood. More specifically, type 1 fibre percentage tends to increase in women (51 ± 9% to 55 ± 12%) and decrease in men (55 ± 12% to 48 ± 13%) between the ages of 16 and 27 years (Bell et al., 1980; Lexell et al., 1992). Therefore, the ability to produce force rapidly in females can be limited hence affecting sprinting performance compared to their male counterparts, post PHV.

## 6. Muscle and tendon stiffness

Apart from muscle size and fibre type composition, tendon stiffness has also been documented to have a positive influence on sprinting performance in children (Lambertz et al., 2003). Increased tendon stiffness leads to shorter braking forces, reduced ground contact times and greater electromyographic activity that can be useful during sprinting (Lazaridis et al., 2010). Previous studies have reported that males have a higher level of stiffness compared to females in the patella and Achilles' tendon (Hicks et al., 2013; Onambele et al., 2007). In youth, Laffaye et al. (2016) found leg stiffness increased from 24.7 ± 10.6 kN · m−1 at 11-12 years to 44.1 ± 14 kN · m−1 in boys, with a small increase until 16 years (+17%) and a large increase between 17 and 20 years (+32.7%). In girls, leg stiffness increased from 26.6 ± 9 kN · m−1 at 11-12 years to 39.4 ± 10.9 kN · m−1 at 19-20 years, with a decrease in leg stiffness at 17-18 years, probably due to an increase in the percentage of fat at this age (25%). However, there are limited studies that have investigated the difference in tendon stiffness in boys and girls across maturation (Laffaye et al., 2016; O'Brien et al., 2010b). Therefore, understanding how growth, maturity and physiological mechanism associated with SSC affects sprinting kinetics and kinematics is crucial when investigating young females.

## 7. Assessment of growth and maturation

It has been established that rapid changes in PHV and PWV can impact sprinting performance in youth (Malina et al., 2004). Therefore, it is important to assess biological growth and not rely only on chronological age alone. The differences in timing and magnitude of growth within similar age groups of girls and boys can have a significant impact on sprinting performance (Lloyd et al., 2016; Malina et al., 2004). For example, two 12-year-old girls may have different sprinting abilities due to their height and body mass.

There are several ways to assess the growth and biological maturity of a child. The most popular clinical method utilises a plain X-ray of the left hand, wrist or knee and classifies children according to their skeletal age (Carling, Le Gall, Reilly, & Williams, 2009; Johnson, Doherty, & Freemont, 2009; Malina et al., 2004). Unfortunately, this method requires expensive equipment and an experienced investigator, thus is impractical for young athletes (Harrison, 2013). The Tanner Staging method, which classifies sexual maturity based on pubic hair development, has also been used widely in the literature (Conte et al., 2017; Faigenbaum et al., 1993; Tanner & Whitehouse, 1976). However, classification requires athletes to self-assess, which can affect the reliability of the measures (Rasmussen et al., 2015). For example, a previous study in Danish children (n = 898) reported that self-assessment and parental assessment were inaccurate in a substantial number of participants when compared with a clinical examination by trained physicians (Rasmussen et al., 2015). More specifically, half the girls tended to underestimate their exact breast development stage, and one quarter also underestimated their pubic hair. Therefore, suggesting that self-assessment of pubertal maturation can be inaccurate and unreliable.

A cheaper, non-invasive way of assessing maturation is by calculating the estimated years an individual is away from PHV. This method provides a maturity offset value using simple objective anthropometric measures, including leg length, sitting height, weight by height ratio and age (Malina et al., 2004; Mirwald, Baxter-Jones, Bailey, & Beunen, 2002). Years from PHV can be used to characterise changes in body size, body composition and performance relative to changes in height (Malina et al., 2004). Maturity status is determined as pre-PHV (>1 year prior to PHV), circa-PHV (± 1 year from PHV), and post-PHV (> 1 year post PHV) and comparisons of any changes in performance can be made (Harrison, 2013). The Khamis-Roche method is another non-invasive and practical way of assessing maturity and includes three predictor variables: current stature (height), current weight and mid parent stature (mother's height + father's height/2) (Khamis & Roche, 1994).

Past research has incorporated the Mirwald and Khamis-Roche methods effectively to measure growth and maturation (Cumming et al., 2018; Rumpf et al., 2012). For example, Rumpf et al. (2012) used the Mirwald method to investigate sprinting kinetics and kinematics across maturation. Similarly, Cumming et al. (2018) used the Khamis-Roche method to predict adult height in a cohort of young soccer players when investigating the efficacy of bio-banding. It is important to assess growth and maturity in research with youth populations to guide safe and effective applications of training.

## 8. Developmental Models

Youth athlete training interventions that consider growth and maturation are essential. To support practitioners in this process, the long-term athletic development model (LTAD) was proposed (Balyi & Hamilton, 2004; Bompa, 1995). The LTAD model attempts to maintain balance between training load and competition throughout childhood and adolescence (Ford et al., 2011). It also proposes specific windows of development, termed "sensitive periods of development" for various components of fitness. When considering speed, the LTAD model suggests two training sensitive periods during childhood (Balyi & Hamilton, 2004), aligned to chronological age. The first period, occurring at 7-9 years in both genders, is aligned to a neurological spurt (Table 1) (Balyi & Hamilton, 2004). According to the LTAD

Table 1: Long term Athletic Development (LTAD): Sensitive periods for speed development (adapted from LTAD model, Balyi & Hamilton, 2005)

| **Speed Developmental Age** | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Chronological Age** | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
| Speed 1 | | | | | | | | | | | | | | |
| Speed 2 (Girls) | | | | | | | | | | | | | | |
| Speed 2 (Boys) | | | | | | | | | | | | | | |

model, a period of accelerated brain development around age 7-9 years improves a child's ability to acquire the motor skill (Balyi & Hamilton, 2004; Higgs et al., 2008) via improvements in coordination (Cratty, 1986). The second sensitive period, occurring at 11-13 and 13-15 years of age in girls and boys, respectively, reflects a maturational window of opportunity for training (Table 1) driven by hormone-dependent hypertrophy of muscle fibres (Phillippaerts et al., 2006; Venturelli, Bishop, & Pettene, 2008; Viru et al., 1999).

However, since the LTAD model's inception, it has been critiqued for a lack of scientific rigour as the sensitive periods of development are based on chronological age as opposed to biological growth and maturity (Ford et al., 2011). For example, several factors influence speed throughout childhood, including quantitative changes in muscle cross-sectional area and length, morphological alterations to the muscle and tendon, development of SSC through neuromuscular pathways, and biomechanical factors associated with sprinting (kinetics and kinematics) (Ford et al., 2011; Radnor et al., 2018). Hence, it is important to consider these factors when investigating the potential of speed development in youth across maturation rather than rely completely on the windows of opportunity based on chronological age. It is also important to note that the majority of research investigating speed development in youth populations has been conducted in boys (Meyers et al., 2015; Meyers et al., 2016; Meyers et al., 2017a; Rumpf et al., 2015). As identified above, considering the emergence of distinct differences in physiology between the sexes with maturation, and their subsequent effects on speed, more research investigating the second LTAD window of training in girls is warranted (Papai et al., 2012).

More recently, using existing empirical research, the Youth Physical Development (YPD) model was proposed (Lloyd & Oliver, 2012). The goal of the YPD model was to establish an overall long-term strategy for physical development across childhood and adolescents. In contrast to the LTAD model, the YPD model proposes that all fitness components are trainable throughout development but that the magnitude of change differs based on maturation (Lloyd et al., 2015). More specifically, the YPD model suggests that speed can be trained at any age with a greater emphasis between 5-15 years for females and 5-16 years for males (Table 2) (Lloyd & Oliver, 2012). Furthermore, the model emphasises individualisation of training prescription due to the differences in timing, tempo, and magnitude of maturation between children (Lloyd et al., 2015). For example, it is believed that the training adaptation during pre PHV phase is predominantly neural compared to a combination of neural and hormonal during mid and post-PHV phases in both males and females (Lloyd & Oliver, 2012). In young males, it was found that plyometric training (PT) was useful in improving sprinting speed during pre-PHV, but a combination of strength training (ST) and PT was more effective during post PHV further supporting the YPD model (Lloyd et al., 2016a) However, more research is warranted if the adaption is similar across maturation in young females.

Despite their differences, both the LTAD and YPD models suggest that biological maturity should be considered when planning individual components of fitness in youth (Ford et al., 2011; Lloyd & Oliver, 2012). Furthermore, child physiology and how it changes with growth, and between the sexes, is important to understand when prescribing speed training in youth (Balyi & Hamilton, 2004; Oliver et al., 2013).

## 9. Determinants of speed: sprint-running performance

Several factors influence sprint performance in youth, including the motions of the body (i.e., kinematics) (Hunter, Marshall, & McNair, 2005; Meyers et al., 2016; Salo et al., 2011), the forces that produce, arrest or modify the motions of the body (i.e., kinetics) (Meylan et al., 2014; Read et al., 2016; Rumpf et al., 2015) and the measurements and proportions of the body (i.e., anthropometry) (Lloyd et al., 2016b; Meyers et al., 2016;

Table 2: Youth Physical Development (YPD): Sensitive periods for speed development (adapted from YPD model, Lloyd & Oliver 2012)

| **Speed Developmental Age** | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Chronological Age** | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
| Girls | | | | | | | | | | | | | | |
| Boys | | | | | | | | | | | | | | |

Meyers et al., 2017b). Since the anthropometrical factors (PHV, PWV, body composition) have already been discussed in the previous sections, this section will specifically review the kinetics and kinematic associated with sprinting speed in young boys and girls across maturation.

### *9.1. Kinematics*

Sprint speed is a product of step length and step frequency (Meyers et al., 2017b). However, the relationship between step length and frequency is not always linear (Meyers et al., 2017b). For instance, research has demonstrated a negative interaction between step length and step frequency in adult sprinters i.e., a longer step length tends to result in a lower step rate (Debaere, Jonkers, & Delecluse, 2013; Coh, Milanovic, & Kammiller, 2001; Hunter et al., 2004). The interaction between step length and step frequency is more difficult to define in youth populations due to changes in natural development (Meyers et al., 2017b). For instance, step length increases throughout childhood and adolescence as a result of changes in leg length associated with growth (Meyers et al., 2016; Schepens, Willems, & Cavagna, 1998). Read et al. (2016) reported a consistent increase in step length among boys who remained pre-PHV and boys moving from pre to post PHV (7.8 and 8%, respectively) compared to step frequency.

Previous research investigating step frequency and flight time indicated that both remain unchanged throughout childhood and in boys of advancing maturity (Meyers et al., 2015; Rumpf et al., 2015; Schepens et al., 1998). Pre-PHV boys tend to be more reliant on step frequency when sprinting (Meyers et al., 2017a), but may lack the motor coordination and strength to orientate, stabilize and apply force through their lower limbs during sprinting (Meyers et al., 2015). Therefore, there may not be any meaningful changes in step frequency and flight time in male youth across maturational levels whereas increases in step length can be observed for boys who have experienced the period of PHV.

Despite a few studies having investigated the effects of change in kinematics on sprint performance in boys, there are currently limited studies in girls. In a recent study, Talukdar and Colleagues (2022) found step length to be significantly greater in post PHV girls compared to mid-PHV girls ($p < 0.05$). It was also reported that there was no difference in contact time, flight time, step frequency between mid- and post PHV girls (Talukdar et al., 2022). In contrast, Nagahara et al. (2019) found that in young (<12.7 years) Japanese girls, step length increased by 0.08m/y but plateaued (0.01 m/y) for the older girls >12.7 years. Similarly, researchers have reported no increase in step length with minimal increase in step frequency among Slovakian girls (mean age 13.5 years) (Vanderka & Kampmiller, 2012). However, both aforementioned studies did not consider maturation and biological growth. Based on chronological age, it is difficult to conclude if growth-related factors (e.g., fat mass, PHV) during puberty played a role. Therefore, more research investigating sprinting kinematics in girls across maturation is warranted.

### *9.2. Kinetics*

The kinetics (horizontal and vertical forces) of sprint performance have been widely investigated in adults (Brughelli, Cronin, & Chaouchi, 2011; Kuitunen, Komi, & Kyrolalinen, 2002; Nilsson & Thorsrensson, 1989; Nummela, Keranen, & Mikkelsson, 2007). Previous studies report that peak and average force increase proportionately to running speed up to 60% of maximum velocity, then remain relatively constant up to maximum velocity (Brughelli et al., 2011; Kyrolainen et al., 2001; Nilsson & Thorstensson, 1989). More specifically, during the acceleration phase, horizontal forces have been shown to significantly increase with increasing speed (Brughelli et al., 2011; Kuitunen et al., 2002; Nummela et al., 2007) and during both braking (i.e., eccentric) and propulsion (i.e., concentric) phases (Kuitunen et al., 2002; Nilsson & Thorstensson, 1989). Peak vertical forces are stable and do not differ between 70 and 100% of maximal velocity (Kuitunen et al., 2002). These studies suggest that horizontal force plays an important role in sprinting, particularly during the initial phases of acceleration to overcome inertia.

While much research has investigated how kinetics effect sprint speed in adults, there is a paucity of research investigating over-ground sprinting in youth (Meyers et al., 2015; Meyers et al., 2016; Meyers et al., 2017b; Rumpf et al., 2015). Studies utilizing non-motorized treadmills suggest that maximal force and power may be important predictors of sprint performance in boys across maturation (Meylan et al., 2014b; Rumpf et al., 2015). More specifically, vertical power has been shown to have a large impact on sprint performance in pre- and mid-PHV boys (Meylan et al., 2014b). Cross-sectional and longitudinal data collected in boys has also shown that vertical stiffness, relative maximal force, and relative leg stiffness contribute to sprint performance (Lloyd et al., 2016b; Meyers et al., 2019; Read et al., 2016).

Sprint kinetics may differ between sexes during childhood and adolescence due to changes in maturity status and growth (Rumpf et al., 2015). For instance, during puberty, higher levels of circulating androgens and growth hormones in boys (Forbes et al., 2009; Ramos Frontera, Llopart, & Feliciano, 1998; Round, Jones, Honour, & Nevill, 1999) increases force production (Rumpf et al., 2015). However, an increase in muscle mass and force-generating capacity can be limited in girls during this time due to the reduced anabolic effect of oestrogen. This difference has been shown to influence strength and power in general by decreasing connective tissue stiffness that can negatively affect sprinting kinetics in girls (Chidi-Ogbolu, & Baar, 2019; Malina et al., 2004).

There are limited studies investigating kinetics in young females (Coyler et al., 2020; Nagahara et al., 2019; Talukdar et al., 2022). Talukdar and colleagues (2022) reported greater horizontal force, maximal power and maximal velocity in post-PHV compared to mid-PHV girls ($p < 0.05$). Moreover, it was also reported that both kinetic and kinematic variables such as ground contact time, maximal power, step frequency, and step length have been shown to predict maximal sprinting speed in girls across maturation with contact time being the best predictor out of all (Talukdar et al., 2022). Nagahara et al. (2019) examined age-related differences in sprinting kinetics in (7.0-15.3 years old Japanese girls) and found an increase in the propulsive impulse of 0.024 Ns/y in the younger Japanese girls compared to -0.010 Ns/y in the older girls. However, the authors did not assess maturity status, choosing to divide the girls into two groups based on chronological age (younger <12.7 years and older >12.7 years). Even though the older girls in this study were significantly quicker than the younger girls for 25 m and 50 m sprints ($p < 0.05$), the propulsive forces during acceleration were significantly greater in younger girls compared to the older girls. This is probably due to greater growth rates in height (6.3 cm/y) in the younger girls and increases in fat mass with maturation in the older girls who might have impaired relative force production during the acceleration phase (Nagahara et al., 2019).

In addition, another recent study investigated GRFs related to sprinting speed in pre-PHV untrained boys and girls (Coyler et al., 2020). It was reported that higher velocities were attributed to greater antero-posterior GRFs across shorter ground contacts in pre-PHV boys (4.5-3.5 years before PHV) compared to (5.5-4.5 years before PHV), effect size (ES: ± 90% CI = 1.63 ± 0.69) (Colyer et al., 2020). In comparison, the increase in maximal velocities in pre-PHV girls (2.5-1.5 years before PHV) compared to (1.5-0.5 years from PHV) were not attributed to the increase in GRFs but rather due to longer ground contact time (ES: ± 90% CI = 1.00 ± 0.78). This study suggested that boys undergo a period of accelerated development in sprinting performance around 4.5-5 years before their PHV whereas rapid development in girls was observed 1.5-2 years before PHV. Furthermore, force-generating capacity in boys can help them better utilise SSC and more effectively reverse braking forces compared to their female counterparts (Colyer et al., 2020).

## 10. Conclusion

There is no difference in sprinting performance between boys and girls during the first decade of life, but things change during puberty. Due to the influence of oestrogen, girls tend to increase body fat mass and reduce connective tissue stiffness compared to boys, negatively impacting sprinting speed. Only a few studies investigating the effect of kinetics and kinematics on sprinting speed in youth populations have included girls. It is reported that sprinting kinetics and kinematics change across maturation and can significantly influence the maximal sprinting speed in girls. More specifically, kinetics and kinematic variables such as ground contact time, maximal power, step frequency, and step length have been shown to predict maximal sprinting speed in girls across maturation. Therefore, incorporating progressive strength and plyometric training along with frequent exposure to sprinting can improve sprinting kinetics and kinematics and increase maximal sprinting speed due to improved force-generating capacity and greater lower extremity tendon stiffness in girls approaching puberty. More research in this area is warranted, particularly studies that assess maturation. Studies that examine more specific kinematic and kinetic variables across maturation are also required.

## Conflict of Interest

The authors declare no conflict of interests.

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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.

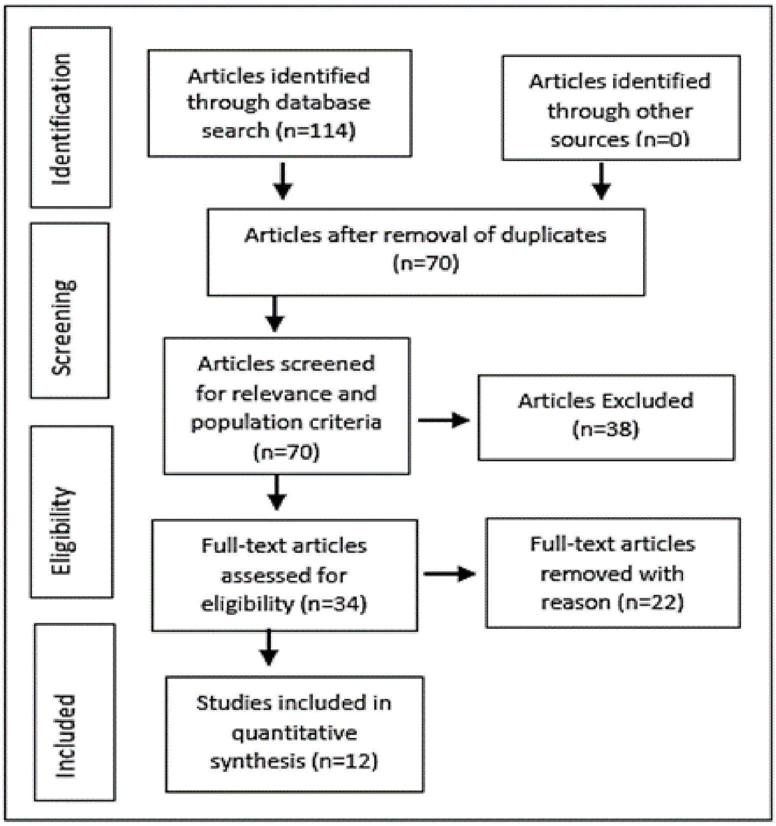


Figure 1: Diagram of study selection for review.

*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<br>Age: 20.4 ± 1.2 years<br>Height: 1.83 ± 0.72m<br>Rugby Union | Custom-manufactured velocimeter (PowerLab4/25T, AD Instruments, Dunedin, NZ).<br>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),<br>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.<br>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<br>Age: 16.7 ± 0.9 years<br>Height: 1.77 ± 0.69m<br>Weight: 75.6 ± 10.9kg<br>Rugby Union<br>Lacrosse | Radar device (Model: Stalker ATS II, Applied Concepts, Dallas, TX, USA) | 1 x un-resisted baseline 20m sprint<br>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<br>Age: 25 ± 3 years<br>Height: 1.86 ± 0.06m<br>Weight: 103.9 ± 10.7kg<br>Rugby Union | Micro-sensor technology units (StatSports Group Limited, Co. Down, Northern Ireland).<br>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,<br>BM Momentum,<br>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. |

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|---|---|---|---|---|---|---|
| Zabaloy et al. 2020 | N=20, Male<br>Age: 22.5 ± 5.3 years<br>Height: 1.80 ± 0.05m<br>Weight: 80.2 ± 15.2kg<br>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.<br>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.<br>Linear position transducer (Chronojump, Boscosystem, Barcelona,Spain).<br>Force Plate (Kistler 9286BA, Winterthur, Switzerland) sampling at 350 Hz. | Day 1: 2x 30 m sprints at each different load.<br>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.<br>1RM Strength | Vmax,<br>Vloss,<br>Max Jump Height,<br>Relative Peak Power,<br>Resultant Mean,<br>Force,<br>Mean Propulsive,<br>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<br>Age: 27.9 ± 1.9<br>Height: 1.76 ± 0.06m<br>Weight: 80.2 ± 9.6kg<br>Mixed Team Sports (basketball, soccer, rugby, baseball, Australian rules football) | Electronic timing light system with double-beam photocells (Swift Performance Equipment, Lismore, Australia).<br>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,<br>Contact time,<br>Toe Off,<br>Foot Strike,<br>Braking,<br>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)<br>Age: 27 ± 4 years<br>Height: 1.76 ± 0.08m<br>Weight: 82.5 ± 10.47kg<br>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.<br>Velocity–time data collected at a rate of 46.9 Hz.<br>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<br>Age: 20.5 ± 2.0 years<br>Height: 1.68 ± 0.65m<br>Weight: 64.8 ± 8.7 kg<br>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. |

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| Cottle et al. 2014 | N=17, n=10 Male, n=7 Female<br>Age: 20.9 ± 1.1 years<br>Height: 1.7 ± 0.1m<br>Weight: 62.2 ± 22.1kg<br>Field & Court sports | AMTI BP400600 force plates (AMTI Watertown, MA, USA) set at 2400 Hz.<br>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<br>Age: 21.1 ± 1.8 years<br>Height: 1.82 ± 0.1m<br>Weight: 83.6 ± 13.1kg<br>Rugby Union & Soccer | Timing gates (Brower Timing System, Utah, USA).<br>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,<br>Stride frequency,<br>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)<br>Age: experimental- 26.3 ± 4.0 years, control- 26.8 ± 4.2 years<br>Height: experimental- 1.77 ± 0.08m, control- 1.75 ± 0.08m<br>Weight: experimental- 74.5 ± 5.3kg, control- 70.7 ± 6.5kg.<br>Soccer | Radar device (Stalker ATS Pro II, Applied Concepts, TX, USA). | 16 sprint sessions over 8 weeks.<br>2 blocks of 5x 20m sprints. | Experimental- 80%BM<br>Control- 0%BM | Velocity,<br>Horizontal GRF,<br>Horizontal power output,<br>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)<br>Age: SLED-26.8 ± 3.0 years, TRAD-25.1 ± 3.2 years<br>Height: SLED-1.86 ± 0.80m, TRAD- 1.85 ± 0.70m<br>Weight: SLED- 90.2 ± 10.3kg, TRAD- 90.9 ± 10.6kg<br>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.<br>SLED- 3x20m resisted sprint<br>TRAD-3x20m unresisted sprint (Pre and Post test of 10 and 30m) | SLED- 12.6% BM<br>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. |

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| **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 ($\mu$ = 0.21-0.58) (Linthorne & Cooper, 2013). In a 30m sled tow sprint with 30%BM, the hockey field (lowest $\mu$) 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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