

ISSN 2703-240X

# *The Journal of* Sport & Exercise Science™



**EDITOR-IN-CHIEF**

Professor Rich Masters

**ASSOCIATE EDITOR-IN-CHIEF**

Associate Professor Matt Driller

**SENIOR SECTION EDITORS**

Professor Jim Cotter

Professor Nick Draper

Professor Chris Button

Professor Andrew Kilding

Professor Michael Hamlin

Associate Professor Melanie Bussey

Associate Professor Kathryn Beck

Associate Professor Carl Paton

Dr Arne Nieuwenhuys

Dr Kathryn Beck

**SE<sup>NS</sup>NZ™**

SPORT & EXERCISE SCIENCE

— NEW ZEALAND —

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

Tāne J. Clement<sup>1</sup>, Keith V. Alexander<sup>2</sup>, Nick Draper<sup>1\*</sup>

<sup>1</sup>*School of Health Sciences, University of Canterbury, Christchurch, New Zealand*

<sup>2</sup>*Department of Mechanical Engineering, University of Canterbury, Christchurch, New Zealand*

### **ARTICLE INFO**

*Received: 07.07.2021*

*Accepted: 22.05.2022*

*Online: 22.08.2022*

**Keywords:**

*Trampoline*

*Cardiovascular Function*

*Vertical Jump*

### **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),  $\dot{V}O_2$ max 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 adaptations 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.

\*Corresponding Author: Nick Draper, School of Health Sciences, University of Canterbury, Christchurch, New Zealand, [nick.draper@canterbury.ac.nz](mailto:nick.draper@canterbury.ac.nz)

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 (Arabatzis, 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  $29 \pm 12$  years. Means of the anthropomorphic measures for males and females were respectively; height ( $180 \pm 3$ cm) ( $164 \pm 5$ cm), mass ( $93 \pm 18$ kg) ( $71 \pm 15$ kg) and BMI ( $29 \pm 7$ ) ( $27 \pm 6$ ). 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  $\dot{V}O_2\max$ , 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  $\dot{V}O_2\max$  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  $\dot{V}O_2\max$  ( $F_{2,26} = 4.185, p = 0.027, \eta_p^2 = 0.2$ ), 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  $\pm$  SD of the variables for the control and intervention groups.

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

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

Table 2: Means  $\pm$  SD of the variables for the intervention group.

	Week 0	Week 4	Week 8
Mass (kg)	78.6 $\pm$ 20.0	78.7 $\pm$ 20.9	78.6 $\pm$ 20.1
Muscle Mass (kg)	30.5 $\pm$ 8.0	30.2 $\pm$ 8.8	30.5 $\pm$ 8.0
Fat Mass (kg)	24.1 $\pm$ 12.8	25.1 $\pm$ 14.1	24.3 $\pm$ 12.7
Systolic Blood Pressure (mmHg)	119 $\pm$ 14	119 $\pm$ 15	114 $\pm$ 14
Diastolic Blood Pressure (mmHg)	74 $\pm$ 7	75 $\pm$ 9	73 $\pm$ 8
Blood Cholesterol (mmol/L)	5.0 $\pm$ 1.3	6.2 $\pm$ 1.4*	5.7 $\pm$ 1.7
Relative $\dot{V}O_2$ (mL/min/kg)	40.2 $\pm$ 8.4	44.1 $\pm$ 7.4*	42.6 $\pm$ 9.9
Vertical Jump (cm)	32 $\pm$ 9	34 $\pm$ 9	36 $\pm$ 9*
Total Jump Height (m)	46 $\pm$ 20.7	61.6 $\pm$ 24.7*	69 $\pm$ 25.7
Time to completion (s)	110 $\pm$ 9	116 $\pm$ 10*	119 $\pm$ 11*
Caloric Expenditure (kcal)	34 $\pm$ 27	45 $\pm$ 43*	50 $\pm$ 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  $44 \pm 8.5$  which then decreased to  $40.9 \pm 9.4$  in Week 4 and decreased again to  $40.8 \pm 7.2$  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%.

JSES | <https://doi.org/10.36905/jses.2022.03.01>

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.

### Acknowledgment

The authors would like to thank the Callaghan Innovation Grant and Springfree trampolines for providing the funding for this project. Grant Number: E6730.

### References

- Aalizadeh, B., Mohammadzadeh, H., Khazani, A., & Dadras, A. (2016). Effect of a trampoline exercise on the anthropometric measures and motor performance of adolescent students. *International Journal of Preventative Medicine*, 7(1), 91. <https://doi.org/10.4103/2008-7802.186225>
- Alexander, K., Clement, T., & Draper, N. (2020). Developing a mathematical model to predict energy expenditure while bouncing on a trampoline. *European Journal of Sport Science*, 21(2), 141-148.
- American College of Sport Medicine. (2013). *ACSM's guidelines for exercise testing and prescription*. Lippincott Williams & Wilkins.
- Arabatzi, F. (2018). Adaptations in movement performance after plyometric training on mini-trampoline in children. *Journal of Sports Medicine and Physical Fitness*, 58(1-2), 66-72.
- Atilgan, O. E. (2013). Effects of trampoline training on jump, leg strength, static and dynamic balance of boys. *Science of Gymnastics Journal*, 5(2), 15-25.
- Berthouze, S., Minaire, P., Castells, J., Busso, T., Vico, L., & Lacour, J.-R. (1995). Relationship between mean habitual daily energy expenditure and maximal oxygen uptake. *Medicine and Science in Sports and Exercise*, 27(8), 1170-1179.
- Clement, T., Alexander, K., & Draper, N. (2020). Investigating the effect of bouncing type on the physiological demands of trampolining. *European Journal of Sport Science*, 21(1), 1-6. <https://doi.org/10.1080/17461391.2020.1721564>
- Crowther, R. G., Spinks, W. L., Leicht, A. S., & Spinks, C. D. (2007). Kinematic responses to plyometric exercises conducted on compliant and noncompliant surfaces. *The Journal of Strength and Conditioning Research*, 21(2), 460-465. <https://doi.org/10.1519/00124278-200705000-00030>
- Cugusi, L., Manca, A., Serpe, R., Romita, G., Bergamin, M., Cadeddu, C., Solla, P., & Mercurio, G. (2016). Effects of a mini-trampoline rebounding exercise program on functional

- parameters, body composition and quality of life in overweight women. *Journal of Sports Medicine and Physical Fitness*, 58(3), 287-294.
- de Villarreal, E. S.-S., Kellis, E., Kraemer, W. J., & Izquierdo, M. (2009). Determining variables of plyometric training for improving vertical jump height performance: a meta-analysis. *The Journal of Strength and Conditioning Research*, 23(2), 495-506.
- Draper, N., Clement, T., & Alexander, K. (2020). Physiological demands of trampolining at different intensities. *Research Quarterly for Exercise and Sport*, 91(1), 136-141.
- Foster, C., Farland, C. V., Guidotti, F., Harbin, M., Roberts, B., Schuette, J., Tuuri, A., Doberstein, S. T., & Porcari, J. P. (2015). The effects of high intensity interval training vs steady state training on aerobic and anaerobic capacity. *Journal of Sports Science and Medicine*, 14(4), 747-755.
- Gerberich, S. G., Leon, A. S., McNally, C., Serfass, R., & Edin, J. B. (1990). Analysis of the acute physiologic effects of minitrampoline rebounding exercise. *Journal of Cardiopulmonary Rehabilitation and Prevention*, 10(11), 395-400.
- Greaney, M. L., Less, F. D., White, A. A., Dayton, S. F., Riebe, D., Blissmer, B., Shoff, S., Walsh, J. R., & Greene, G. W. (2009). College students' barriers and enablers for healthful weight management: A qualitative study. *Journal of Nutrition Education and Behavior*, 41(4), 281-286. <https://doi.org/10.1016/j.jneb.2008.04.354>
- Hamlin, M., Draper, N., Blackwell, G., Shearman, J., & Kimber, N. (2012). Determination of maximal oxygen uptake using the Bruce or a novel athlete-led protocol in a mixed population. *Journal of Human Kinetics*, 31, 97-104.
- Hooper, L., Summerbell, C. D., Higgins, J. P., Thompson, R. L., Capps, N. E., Smith, G. D., Riemersma, R. A., & Ebrahim, S. (2001). Dietary fat intake and prevention of cardiovascular disease: systematic review. *BMJ*, 322(7289), 757-763.
- Iwasaki, K.-i., Zhang, R., Zuckerman, J. H., & Levine, B. D. (2003). Dose-response relationship of the cardiovascular adaptation to endurance training in healthy adults: how much training for what benefit? *Journal of Applied Physiology*, 95(4), 1575-1583.
- Kannel, W. B., Castelli, W. P., Gordon, T., & McNamara, P. M. (1971). Serum cholesterol, lipoproteins, and the risk of coronary heart disease. *Annals of Internal Medicine*, 74(1), 1-12. <https://doi.org/10.7326/0003-4819-74-1-1>
- Lawlor, D. A., & Hopker, S. W. (2001). The effectiveness of exercise as an intervention in the management of depression: systematic review and meta-regression analysis of randomised controlled trials. *BMJ*, 322(7289), 763-767.
- Lukaski, H. C., Johnson, P. E., Bolonchuk, W. W., & Lykken, G. I. (1985). Assessment of fat-free mass using bioelectrical impedance measurements of the human body. *American Journal of Clinical Nutrition*, 41(4), 810-817.
- Marques, E. A., Mota, J., & Carvalho, J. (2012). Exercise effects on bone mineral density in older adults: a meta-analysis of randomized controlled trials. *Age*, 34(6), 1493-1515. <https://doi.org/10.1007/s11357-011-9311-8>
- McGlone, C., Kravitz, L., & Janot, J. M. (2002). Rebounding: A low-impact exercise alternative. *ACSM's Health & Fitness Journal*, 6(2), 11-15.
- McGowan, C. J., Pyne, D. B., Thompson, K. G., & Rattray, B. (2015). Warm-up strategies for sport and exercise: mechanisms and applications. *Sports Medicine*, 45(11), 1523-1546.
- McIntyre, L., & Dutton, M. (2015). *Eating and Activity Guidelines for New Zealand Adults*. Ministry of Health.
- Nocon, M., Hiemann, T., Müller-Riemenschneider, F., Thalau, F., Roll, S., & Willich, S. N. (2008). Association of physical activity with all-cause and cardiovascular mortality: a systematic review and meta-analysis. *European Journal of Cardiovascular Prevention & Rehabilitation*, 15(3), 239-246.
- Nuhu, J., & Maharaj, S. (2017). Influence of a mini trampoline rebound exercise program on insulin resistance, lipid profile and central obesity in individuals with type 2 diabetes. *Journal of Sports Medicine and Physical Fitness*, 58(4), 503-509.
- Ramos, J. S., Dalleck, L. C., Tjonna, A. E., Beetham, K. S., & Coombes, J. S. (2015). The impact of high-intensity interval training versus moderate-intensity continuous training on vascular function: a systematic review and meta-analysis. *Sports Medicine*, 45(5), 679-692.
- Rogers, M. A., & Evans, W. J. (1993). Changes in skeletal muscle with aging: effects of exercise training. *Exercise and Sport Sciences Reviews*, 21, 65-102.
- Ross, A. L., & Hudson, J. L. (1997). Efficacy of a mini-trampoline program for improving the vertical jump. *Biomechanics in Sports XV*, 63-69.
- Şahin, G., Demir, E., & Aydın, H. (2016). Does mini-trampoline training more effective than running on body weight, body fat, VO 2 max and vertical jump in young men? *International Journal of Sports Science*, 6(1), 1-5.
- Schutzer, K. A., & Graves, B. S. (2004). Barriers and motivations to exercise in older adults. *Preventive Medicine*, 39(5), 1056-1061.
- Shellock, F. G., & Prentice, W. E. (1985). Warming-up and stretching for improved physical performance and prevention of sports-related injuries. *Sports Medicine*, 2(4), 267-278.
- Stojanović, E., Ristić, V., McMaster, D. T., & Milanović, Z. (2017). Effect of plyometric training on vertical jump performance in female athletes: a systematic review and meta-analysis. *Sports Medicine*, 47(5), 975-986.
- Tambalis, K., Panagiotakos, D. B., Kavouras, S. A., & Sidossis, L. S. (2009). Responses of blood lipids to aerobic, resistance, and combined aerobic with resistance exercise training: a systematic review of current evidence. *Angiology*, 60(5), 614-632.
- Wewege, M., Van Den Berg, R., Ward, R., & Keech, A. (2017). The effects of high - intensity interval training vs. moderate - intensity continuous training on body composition in overweight and obese adults: a systematic review and meta - analysis. *Obesity Reviews*, 18(6), 635-646.
- Zhao, R., Zhao, M., & Zhang, L. (2014). Efficiency of jumping exercise in improving bone mineral density among premenopausal women: a meta-analysis. *Sports Medicine*, 44(10), 1393-1402.

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

Kaushik Talukdar<sup>1,2,3</sup>, Craig Harrison<sup>2</sup>, Mike R. McGuigan<sup>2,4</sup>

<sup>1</sup>*Athlete Institute, Auckland, New Zealand*

<sup>2</sup>*Sports Performance Research Institute of New Zealand, Auckland, New Zealand*

<sup>3</sup>*Faculty of Health and Environmental Sciences, Auckland University of Technology, New Zealand*

<sup>4</sup>*School of Medical and Health Sciences Edith Cowan University, Australia*

### ARTICLE INFO

Received: 16.02.2022

Accepted: 16.06.2022

Online: 22.08.2022

### Keywords:

Sprinting

Youth

Growth

### 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

\*Corresponding Author: Kaushik Talukdar, Athlete Institute, New Zealand, Kaushik.talukdar21@gmail.com

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 ( $0.24$  m/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 170ms (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 ( $51 \pm 9\%$  to  $55 \pm 12\%$ ) and decrease in men ( $55 \pm 12\%$  to  $48 \pm 13\%$ ) 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  $24.7 \pm 10.6 \text{ kN} \cdot \text{m}^{-1}$  at 11-12 years to  $44.1 \pm 14 \text{ kN} \cdot \text{m}^{-1}$  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  $26.6 \pm 9 \text{ kN} \cdot \text{m}^{-1}$  at 11-12 years to  $39.4 \pm 10.9 \text{ kN} \cdot \text{m}^{-1}$  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 ( $\pm 1$  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, & Kyrolainen, 2002; Nilsson & Thorstensson, 1989; Nummela, Keranen, & Mikkelsen, 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 (Coyle 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 (Colyer 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:  $\pm 90\%$  CI =  $1.63 \pm 0.69$ ) (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:  $\pm 90\%$  CI =  $1.00 \pm 0.78$ ). 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.

## Acknowledgement

This is to acknowledge that there was no financial interest or benefit that has arisen from the direct applications of our research.

## References

- Balyi, I., & Hamilton, A. (2004). Long-term athlete development: Trainability in childhood and adolescence. *Olympic Coach*, 16(1), 4-9.
- Barnes, H. V. (1975). Physical growth and development during puberty. *Medical Clinics of North America*, 59, 1305-1317.
- Bell, R. D., MaCdougall, J. D., Billeter, R., & Howald, H. (1980). Muscle fiber types and morphometric analysis of skeletal muscle in six-year-old children. *Medicine and Science in Sports and Exercise*, 12(1), 28-31.
- Beunen, G., & Malina, R. M. (1988). Growth and physical performance relative to the timing of the adolescent spurt. *Exercise and Sport Sciences Reviews*, 16(1), 503-540. <https://doi.org/10.1249/00003677-198800160-00018>
- Bompa, T. O. (1995). *From childhood to champion athlete*. West Sedona, AZ: Veritas Publishing.
- Borms, J. (1986). The child and exercise: an overview. *Journal of Sports Sciences*, 4(1), 3-20. <https://doi.org/10.1080/02640418608732093>
- Brown, K. A., Patel, D. R., & Darmawan, D. (2017). Participation in sports in relation to adolescent growth and development. *Translational Pediatrics*, 6(3), 150-159. <https://doi.org/10.21037/tp.2017.04.03>
- Brughelli, M., Cronin, J., & Chaouachi, A. (2011). Effects of running velocity on running kinetics and kinematics. *Journal of Strength and Conditioning Research*, 25(4), 933-939. <https://doi.org/10.1519/JSC.0b013e3181c64308>
- Butterfield, S. A., Lehnhard, R., Lee, J., & Coladarci, T. (2004). Growth rates in running speed and vertical jumping by boys and girls ages 11-13. *Perceptual and Motor Skills*, 99(1), 225-234. <https://doi.org/10.2466/pms.99.1.225-234>
- Carling, C., Le Gall, F., Reilly, T., & Williams, A. M. (2009). Do anthropometric and fitness characteristics vary according to birth date distribution in elite youth academy soccer players? *Scandinavian Journal of Medicine and Science in Sports*, 19(1), 3-9. <https://doi.org/10.1111/j.1600-0838.2008.00867.x>
- Chidi-Ogbolu, N., & Baar, K. (2019). Effect of oestrogen on musculoskeletal performance and injury risk. *Frontiers in Physiology* 9, 1834. <https://doi.org/10.3389/fphys.2018.01834>
- Čoh, M., Milanović, D., & Kampmiller, T. (2001). Morphologic and kinematic characteristics of elite sprinters. *Collegium Antropologicum*, 25(2), 605-610.
- Colyer, S. L., Nagahara, R., Takai, Y., & Salo, A. I. T. (2020). The effect of biological maturity status on ground reaction force production during sprinting. *Scandinavian Journal of Medicine and Science in Sports*, 30(8), 1387-1397.
- Conte, D., Favero, T., Niederhausen, M., Carpranica, L., & Tessitore, A. (2017). Effect of number of players and maturity on ball-drills training load in youth basketball. *Sports*, 5(3), 1-11. <https://doi.org/10.3390/sports5010003>
- Cratty, B.J. (1986). *Perpetual motor development in infants and children* (3<sup>rd</sup> Ed). Englewood Cliffs, NJ: Prentice-Hall.

- Cumming, S. P., Brown, D. J., Mitchell, S., Bunce, J., Hunt, D., Hedges, C., Crane, G., Gross, A., Scott, S., Franklin, E., Breakspear, D., Dennison, L., White, P., Cain, A., Eisenmann, J. C., & Malina, R. M. (2018). Premier League academy soccer players' experiences of competing in a tournament bio-banded for biological maturation. *Journal of Sports Sciences*, 36(7), 757–765.
- Debaere, S., Jonkers, I., & Delecluse, C. (2013). The contribution of step characteristics to sprint running performance in high-level male and female athletes. *Journal of Strength and Conditioning Research*, 27(1), 1164–1224. <https://doi.org/10.1519/JSC.0b013e31825183ef>
- Faigenbaum, A. D., Zaichkowsky, L. D., Wescott, W. L., Micheli, L.J., & Fehlandt, A. F. (1993). The effect of a twice-a-week strength training program on children. *Pediatric Exercise Science*, 5, 339-346.
- Flanagan, E. P., & Comyns, T. (2008). The use of contact time and the reactive index to optimize fast stretch shortening cycle training. *Strength and Conditioning Journal*, 30(5), 32-38. doi: 10.1519/SSC.0b013e318187e25b
- Ford, P., De Ste Croix, M., Lloyd, R., Meyers, R., Moosavi, M., Oliver, J., Till, K., & Williams, C. (2011). The long-term athlete development model: Physiological evidence and application. *Journal of Sports Sciences*, 29(4), 389–402. <https://doi.org/10.1080/02640414.2010.536849>
- Harrison, C. B. (2013). *Optimisation of aerobic fitness development in young athletes* (Doctoral dissertation, Auckland University of Technology). Retrieved from <https://aut.researchgateway.ac.nz/bitstream/handle/10292/7877/HarrisonC.pdf?sequence=3&isAllowed=y>.
- Hicks, K. M., Onambele-Pearson, G. L., Winwood, K., & Morse, C. I. (2013). Gender differences in fascicular lengthening during eccentric contractions: The role of the patella tendon stiffness. *Acta Physiologica*, 209(3), 235–244. <https://doi.org/10.1111/apha.12159>
- Higgs, C., Balyi, I., Way, R., Cardinal, C., Norris, S., & Bluehardt, M. (2008). Developing physical literacy: A guide for parents of children ages 0 to 12. *Vancouver, BC: Canadian Sports Centres*. <https://doi.org/10.3868/s110-003-014-0039-x>
- Hoffman, A.D. (1997). Adolescent growth and development. In A.D. Hoffman & D. E. Greydanus (Eds.), *Adolescent Medicine* (pp.11-22). Stanford, CT: Appleton & Lange. <https://doi.org/10.1111/apha.12159>
- Hunter, J. P., Marshall, R. N., & McNair, P. J. (2005). Relationships between ground reaction force impulse and kinematics of sprint-running acceleration. *Journal of Applied Biomechanics*, 21(1), 31–43. <https://doi.org/10.1123/jab.21.1.31>
- Johnson, A., Doherty, P. J., & Freemont, A. (2009). Investigation of growth, development, and factors associated with injury in elite schoolboy footballers: Prospective study. *British Medical Journal*, 338(b490), 1-4. <https://doi.org/10.1136/bmj.b490>
- Khamis, H. J., & Roche, A. F. (1994). Predicting adult stature without using skeletal age: The Khamis-Roche method. *Pediatrics*, 95(3), 504–507.
- Komi, P. V. (2000). Stretch-shortening cycle: A powerful model to study normal and fatigued muscle. *Journal of Biomechanics*, 33(10), 1197–1206. [https://doi.org/10.1016/S0021-9290\(00\)00064-6](https://doi.org/10.1016/S0021-9290(00)00064-6)
- Kreipe, R. E. (1994). Normal somatic adolescent growth and development. In McAnarney E. R., Kreipe, R. E, Orr, D. P (Eds), *Textbook of adolescent medicine*, (pp. 44-67). Philadelphia: WB Saunders.
- Kubo, K., Kanehisa, H., Kawakami, Y., & Fukanaga, T. (2001). Growth changes in the elastic properties of human tendon structures. *International Journal of Sports Medicine*, 22(2), 138-43. <https://doi.org/10.1055/s-2001-11337>
- Kuitunen, S., Komi, P. V., & Kyröläinen, H. (2002). Knee and ankle joint stiffness in sprint running. *Medicine and Science in Sports and Exercise*, 34(1), 166–173. <https://doi.org/10.1097/00005768-200201000-00025>
- Kyrolainen, H., Belli, A., & Komi, P. V. (2001). Biomechanical factors affecting running economy. *Medicine and Science in Sports and Exercise*, 33(8), 1330-7. <https://doi.org/10.1097/00005768-200108000-00014>
- Laffaye, G., Choukou, M. A., Benguigui, N., & Padulo, J. (2016). Age- and gender-related development of stretch-shortening cycle during a sub-maximal hopping task. *Biology of Sport*, 33(1), 29–35. <https://doi.org/10.5604/20831862.1180169>
- Lambertz, D., Mora, I., Grosset, J. F., & Pérot, C. (2003). Evaluation of musculotendinous stiffness in prepubertal children and adults, taking into account muscle activity. *Journal of Applied Physiology*, 95(1), 64–72. <https://doi.org/10.1152/jappphysiol.00885.2002>
- Lazaridis, S., Bassa, E., Patikas, D., Giakas, G., Gollhofer, A., & Kotzamanidis, C. (2010). Neuromuscular differences between prepubescents boys and adult men during drop jump. *European Journal of Applied Physiology*, 110(1), 67–74. <https://doi.org/10.1007/s00421-010-1452-4>
- Lazaridis, S., Bassa, E., Patikas, D., Giakas, G., Gollhofer, A., & Kotzamanidis, C. (2010). Neuromuscular differences between prepubescents boys and adult men during drop jump. *European Journal of Applied Physiology*, 110(1), 67–74. <https://doi.org/10.1007/s00421-010-1452-4>
- Lexell, J., Sjöström, M., Nordlund, A. -S, & Taylor, C. C. (1992). Growth and development of human muscle: A quantitative morphological study of whole vastus lateralis from childhood to adult age. *Muscle & Nerve*, 15(3), 404–409. <https://doi.org/10.1002/mus.880150323>
- Lloyd, R. S., & Oliver, J. L. (2012). The youth physical development model: A new approach to long-term athletic development. *Strength and Conditioning Journal*, 34(3), 61–72. <https://doi.org/10.1519/SSC.0b013e31825760ea>
- Lloyd, R. S., Meyers, R. W., Hughes, M. G., Cronin, J. B., & Oliver, J. L. (2016b). The relationship between vertical and horizontal stiffness and maximal running speed in 11–15 year old boys. *Journal of Strength and Conditioning Research*, 30, S99.
- Lloyd, R. S., Oliver, J. L., Faigenbaum, A. D., Howard, R., De Ste Croix, M. B. A., Williams, C. A., Best, T. M., Alvar, B. A., Micheli, L. J., Thomas, D. P., Hatfield, D. L., Cronin, J. B., & Myer, G. D. (2015). Long-term athletic development- Part 1: A pathway for all youth. *Journal of Strength and Conditioning Research*, 29(5), 1439–1450. <https://doi.org/10.1519/JSC.0000000000000756>

- Lloyd, R. S., Oliver, J. L., Hughes, M. G., & Williams, C. A. (2009). Reliability and validity of field-based measures of leg stiffness and reactive index in youths. *Journal of Sports Science*, 27(14), 1565-73. <https://doi.org/10.1080/02640410903311572>
- Lloyd, R. S., Radnor, J. M., Croix, M. B. D. S., Cronin, J. B., & Oliver, J. L. (2016a). Changes in sprint and jump performances after traditional, plyometric, and combined resistance training in male youth pre-and post-peak height velocity. *Journal of Strength & Conditioning Research*, 30(5), 1239-1247.
- Malina, R. M., Bouchard, C., & Bar-Or, O. (2004). *Growth, maturation, and physical activity*. Human kinetics.
- McLellan, C. P., Lovell, D. I., & Gass, G. C. (2011). The role of rate of force development on vertical jump performance. *Journal of Strength and Conditioning Research*, 25(2), 379–385. <https://doi.org/10.1519/JSC.0b013e3181be305c>
- Meyers, R. W., Moeskops, S., Oliver, J. L., Hughes, M. G., Cronin, J. B., & Lloyd, R. S. (2019). Lower-Limb Stiffness and Maximal Sprint Speed in 11-16-Year-Old Boys. *Journal of Strength and Conditioning Research*, 33(7), 1987–1995. <https://doi.org/10.1519/JSC.0000000000002383>
- Meyers, R. W., Oliver, J. L., Hughes, M. G., Cronin, J. B., & Lloyd, R. S. (2015). Maximal sprint speed in boys of increasing maturity. *Pediatric Exercise Science*, 27(1), 85–94. <https://doi.org/10.1123/pes.2013-0096>
- Meyers, R. W., Oliver, J. L., Hughes, M. G., Lloyd, R. S., & Cronin, J. B. (2017a). Influence of age, maturity and body size on the spatiotemporal determinants of maximal sprint speed in boys. *Journal of Strength and Conditioning Research*, 31(4), 1009-1016.
- Meyers, R. W., Oliver, J. L., Hughes, M. G., Lloyd, R. S., & Cronin, J. B. (2017b). New insights into the development of maximal sprint speed in male youth. *Strength and Conditioning Journal*, 39(2), 2–10.
- Meyers, R., Oliver, J., Hughes, M. G., Lloyd, R. S., & Cronin, J. B. (2016). The influence of maturation on sprint performance in boys over a 21-month period. *Medicine of Science in Sport and Exercise*, 48(12), 2555–2562.
- Meylan, C. M. P., Cronin, J., Oliver, J. L., Hopkins, W. G., & Pinder, S. (2014b). Contribution of vertical strength and power to sprint performance in young male athletes. *International Journal of Sports Medicine*, 35(9), 749-754.
- Mirwald, R. L., Baxter-Jones, A. D. G., Bailey, D. A., & Beunen, G. P. (2002). An assessment of maturity from anthropometric measurements. *Medicine and Science in Sports and Exercise*, 34(4), 689–694.
- Morse, C. I., Tolfrey, K., Thom, J. M., Vassilopoulos, V., Maganaris, C. N., & Narici, M. V. (2008). Gastrocnemius muscle specific force in boys and men. *Journal of Applied Physiology*, 104(2), 469–474.
- Nagahara, R., Haramura, M., Takai, Y., Oliver, J. L., Wichitaksorn, N., Sommerfield, L. M., & Cronin, J. B. (2019). Age-related differences in kinematics and kinetics of sprinting in young female. *Scandinavian Journal of Medicine and Science in Sports*, 29, 800–807. <https://doi.org/10.1111/sms.13397>
- Needleman, R. D. (2000). Growth and development, In R.E. Behrman, R.M. Kliegman & H.B. Jenson (Eds.), *Nelson Textbook of Pediatrics* (16<sup>th</sup> Ed). Philadelphia: W B Saunders.
- Nicol, C., Avela, J., & Komi, P. (2006). The stretch shortening cycle: a model to study naturally occurring neuromuscular fatigue. *Sports Medicine*, 36, 977-99.
- Nilsson, J., & Thorstensson, A. (1989). Ground reaction forces at different speeds of human walking and running. *Acta Physiologica Scandinavica*, 136(2), 217–227.
- Nummela, A., Keränen, T., & Mikkelsen, L. O. (2007). Factors related to top running speed and economy. *International Journal of Sports Medicine*, 28(08), 655–661.
- O'Brien, T. D., Reeves, N. D., Baltzopoulos, V., Jones, D. A., & Maganaris, C. N. (2010a). In vivo measurements of muscle specific tension in adults and children. *Experimental Physiology*, 95(1), 202–210.
- O'Brien, T. D., Reeves, N. D., Baltzopoulos, V., Jones, D. A., & Maganaris, C. N. (2010b). Muscle–tendon structure and dimensions in adults and children. *Journal of Anatomy*, 216(5), 631–642.
- Oliver, J. L., Lloyd, R. S., & Rumpf, M. C. (2013). Developing speed throughout childhood and adolescence: The role of growth, maturation and training. *Strength and Conditioning Journal*, 35(3), 42–48.
- Onambélé, G. N. L., Burgess, K., & Pearson, S. J. (2007). Gender-specific in vivo measurement of the structural and mechanical properties of the human patellar tendon. *Journal of Orthopaedic Research*, 25(12), 1635–1642.
- Pápai, J., Tróznai, Z., Szabó, T., & Szabó, A. (2012). Fat pattern of athlete and non-athlete girls during puberty. *Anthropological Review*, 75(1), 41–50.
- Patel, D. R., Pratt, H. D., & Greydanus, D. E. (1998). Adolescent growth, development, and psychosocial aspects of sports participation: an overview. *Adolescent Medicine*, 9(3), 425–440.
- Philippaerts, R. M., Vaeyens, R., Janssens, M., Van Renterghem, B., Matthys, D., Craen, R., Bourgois, J., Vrijens, J., Beunen, G., & Malina, R. M. (2006). The relationship between peak height velocity and physical performance in youth soccer players. *Journal of Sports Sciences*, 24(3), 221–230.
- Radnor, J. M., Oliver, J. L., Waugh, C. M., Myer, G. D., Moore, I. S., & Lloyd, R. S. (2018). The influence of growth and maturation on stretch-shortening cycle function in youth. *Sports Medicine*, 48(1), 57–71.
- Ramos, E., Frontera, W. R., Llopart, A., & Feliciano, D. (1998). Muscle strength and hormonal levels in adolescents: gender related differences. *International Journal of Sports Medicine*, 19(08), 526–531.
- Rasmussen, A. R., Wohlfahrt-Veje, C., De Renzy-Martin, K. T., Hagen, C. P., Tinggaard, J., Mouritsen, A., Mieritz, M. G., & Main, K. M. (2015). Validity of self-assessment of pubertal maturation. *Pediatrics*, 135(1), 86–93.
- Read, P., Meyers, R.W., Lloyd, R.S., Hughes, M.G., Cronin, J.B., & Oliver, J.L. (2016, July). *The impact of peak height velocity on changes in sprint kinetics and kinematics in boys*. In: National Strength and Conditioning Association (NSCA) 39th National Conference, New Orleans, LA.

- Roemmich, J. N., & Rogol, A. D. (1995). Physiology of growth and development: its relationship to performance in the young athlete. *Clinics in Sports Medicine, 14*(3), 483-502.
- Round, J. M., Jones, D. A., Honour, J. W., & Nevill, A. M. (1999). Hormonal factors in the development of differences in strength between boys and girls during adolescence: A longitudinal study. *Annals of Human Biology, 26*(1), 46–62. <https://doi.org/10.1080/030144699282976>
- Rumpf, M. C., Cronin, J. B., Oliver, J., & Hughes, M. (2015). Kinematics and kinetics of maximum running speed in youth across maturity. *Pediatric Exercise Science, 27*(2), 277–284. <https://doi.org/10.1123/pes.2014-0064>
- Rumpf, M. C., Cronin, J. B., Pinder, S. D., Oliver, J., & Hughes, M. (2012). Effect of different training methods on running sprint times in male youth. *Pediatric Exercise Science, 24*(2), 170–186. <https://doi.org/10.1123/pes.24.2.170>
- Salo, A. I. T., Bezodis, I. N., Batterham, A. M., & Kerwin, D. G. (2011). Elite sprinting: are athletes individually step-frequency or step-length reliant? *Medicine & Science in Sports & Exercise, 43*(6), 1055–1062.
- Schepens, B., Willems, P. A., & Cavagna, G. A. (1998). The mechanics of running in children. *Journal of Physiology, 509*, 927–940. <https://doi.org/10.1111/j.1469-7793.1998.927bm.x>
- Talukdar, K., Harrison, C., McGuigan, M., & Borotkanics, R. (2021). Kinetics and kinematics of sprinting in mid-and-post peak height velocity female athletes. *International Journal of Strength and Conditioning, 1*(1). <https://doi.org/10.47206/ijsc.v1i1.65>
- Tanner, J. M., & Whitehouse, R. H. (1976). Clinical longitudinal standards for height, weight, height velocity, weight velocity, and stages of puberty. *Archives of Disease in Childhood, 51*(3), 170–179.
- Tillin, N. A., Pain, M. T. G., & Folland, J. (2013). Explosive force production during isometric squats correlates with athletic performance in rugby union players. *Journal of Sports Sciences, 31*(1), 66–76.
- Turner, A., & Jeffreys, I. (2010). The stretch-shortening cycle: Proposed mechanisms and methods for enhancement. *Strength and Conditioning Journal, 32*(4), 87-99. <https://doi.org/10.1519/SSC.0b013e3181e928f9>
- Underwood, L.E., & Van Wyk, J.J. (1985). Normal and aberrant growth. In *Williams Textbook of Endocrinology, 7th edit*, Eds: Wilson, J.D. and Foster, D.W. Philadelphia: W.B. Saunders.
- Vanderka, M., & Kampmiller, T. (2012). Age-related changes of running stride kinematics in 7 to 18 year old youth. *Exercise and Quality of Life, 4*(1), 11-24.
- Venturelli, M., Bishop, D., & Pettene, L. (2008). Sprint training in preadolescent soccer players. *International Journal of Sports Physiology and Performance, 3*(4), 558–562.
- Viru, A., Loko, J., Harro, M., Volver, A., Laaneots, L., & Viru, M. (1999). Critical periods in the development of performance capacity during childhood and adolescence. *European Journal of Physical Education, 4*(1), 75–119.
- Whithall, J. (2003). Development of locomotor co-ordination and control in children. In G.J.P. Savelsberg, K., Davids, & J. Van der Kamp (Eds.), *In Development of movement coordination in children: Applications in the field of ergonomics, health sciences and sport* (pp. 251-270). London: Routledge.

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

Kristy-Anne Earnshaw<sup>1\*</sup>, Matt Brughelli<sup>1</sup>, Aaron Uthoff<sup>1</sup>

<sup>1</sup>*Sports Performance Research Institute New Zealand, Auckland University of Technology, Faculty of Health and Environmental Science, Auckland, New Zealand*

---

### ARTICLE INFO

Received: 24.08.2021

Accepted: 28.02.2022

Online: 08.09.2022

---

#### Keywords:

Sled Tow

Resisted Sprinting

Sprint Assessment

Sprint Technology

Athlete Monitoring

---

---

### ABSTRACT

*The use of resisted sled towing to enhance sprint capabilities has become one of the most common forms of training in the past decade due to its ability to develop phase-specific mechanical and muscular sprint capabilities. 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 ( $F_0$ ), theoretical maximum velocity ( $V_0$ ), and maximal power output ( $P_{max}$ ) (Pantoja et al., 2018).  $F_0$  and  $F_{max}$  are linked to the initial acceleration phase (0-5 m),  $V_0$  is linked to the maximal velocity an athlete can produce in the absence of mechanical resistances, and  $P_{max}$  is the ability of the athlete to produce the maximal combination of  $F_0$  and  $V_0$  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

---

\*Corresponding Author: Kristy-Anne Earnshaw, Auckland University of Technology, New Zealand, kristyearnshaw1@hotmail.com

(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.

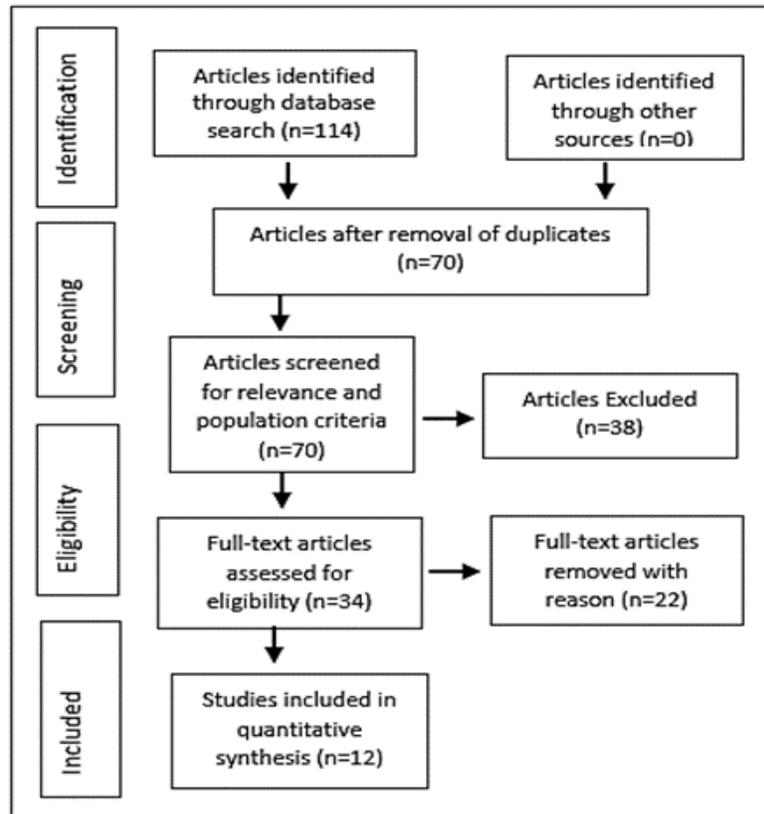


Figure 1: Diagram of study selection for review.

### 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  $1.80 \pm 0.80$  y (Cahill, Oliver et al., 2019). Female participants ages fell between 18.5 and  $27.1 \pm 2.30$  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  $64.8 \pm 8.70$  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  $1.76 \pm 0.36$  to  $1.83 \pm 0.72$ m. The female-only article reported female height as  $1.68 \pm 0.65$ m (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  $V_0$ ,  $F_0$ ,  $P_{max}$ ,  $F-V$  slope, and relative  $F-V$  slope ( $CV \leq 10\%$  &  $ICC \geq 0.75$ ), while 2-10m split times are considered moderately reliable for relative  $F_0$ , and relative  $P_{max}$  (Simperingham et al., 2019). This is thought to be due to the introduction of and increases of angle error (15° 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  $V_{max}$ ,  $V_{dec}$ , 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),  $V_{max}$ , 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  $\pm 0.06$  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  $\geq 500$  (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-  $0.8 \pm 0.6\%$ , RMS error  $1.5 \pm 1.4\%$ , horizontal

peak force-  $-10.8 \pm 2.7$  to  $-18.7 \pm 9.0\%$ , RMS error  $10.8 \pm 2.7$  to  $18.7 \pm 9.0\%$ , vertical impulse-  $0.8 \pm 0.8$  to  $1.2 \pm 0.8\%$ , RMS error  $1.0 \pm 0.4$  to  $1.3 \pm 0.7\%$ , horizontal impulse-  $-9.6 \pm 2.5$  to  $-11.0 \pm 2.8\%$ , RMS error  $9.6 \pm 2.5$  to  $11.0 \pm 2.8\%$  (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/imbalance 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  $V_{max}$ , 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  $V_{max}$  over a resisted 40m sprint. Research has shown that the assessment of  $V_{max}$  from a 40m sprint is considered valid using GPS at 10Hz when compared to a 50Hz radar gun with a mean bias of  $<0.19$  being trivial ( $<0.19$  = trivial,  $0.2-0.59$  = small,  $0.6-1.19$  = medium,  $1.2-1.99$  = big) (Roe et al., 2017). However, there is also research during unresisted sprinting contradicting this, with typical error ranging from 3-15% and ICC ranging from 0.93-0.96%, suggesting that GPS may not have acceptable validity as differences as small as 2% in sprint velocity error are equal to the difference between the 50th and 70th percentile (small effect magnitude) in team sport male athletes for a 20-m unresisted sprint (Haugen & Buchheit, 2016; Johnston et al., 2012; Varley et al., 2012). The validity and reliability of GPS technologies are primarily affected by sprint velocity, sample rate, sprint distance, and movement patterns, i.e., the higher sprint velocity is or the lower the sample rate is, the lower the validity and reliability will be, suggesting that sled tow sprints may have higher GPS validity/reliability due to the reduction in sprint velocity (Haugen & Buchheit, 2016; Johnston et al., 2012). Therefore, more research needs to be undertaken to determine the validity and reliability for GPS during sled tow sprints, particularly as future developments occur with GPS technologies (Haugen & Buchheit, 2016).

In regards to limitations, it should be noted that GPS is limited to outdoor use only as it requires a direct signal to a satellite. This ultimately rules out the use of GPS in court sports, however, GPS technology use in field-sports is dramatically increasing because of its ability to provide real-time and in-game feedback to coaches (Haugen & Buchheit, 2016; Roe et al., 2017; Tierney et al., 2019). Coaches should take into consideration the Hz used and the environment (outdoors) when planning to utilise GPS technology.

## 5. Methodologies

### 5.1. Evaluation Protocols

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

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

Study	Participants	Measurement Technology	Evaluation Protocol	Load	Variables	Results
Cochrane & Monaghan, 2018	N=12, Male Age: 20.4 ± 1.2 years Height: 1.83 ± 0.72m Rugby Union	Custom-manufactured velocimeter (PowerLab4/25T, AD Instruments, Dunedin, NZ). EMG	2x 20m baseline un-resisted sprints, 2x 20m resisted sprints, 20m un-resisted sprints at 2, 4, 6, 8, 12, and 16 minutes of recovery. Velocity taken at 5, 10, 15, and 20m	Initial load of 75% and 115% BM, 35% and 55% Vdec	Maximum Velocity (ms-1), PAP	Sled loads reducing maximal velocity by 35%, improved velocity at 20m ( $p = 0.05$ , $ES = 0.21$ ) compared with 55%, no significant change at 5, 10, or 15m. A significant decline in velocity occurred at 12 ( $p = 0.01$ , $ES = 20.61$ ) and 16 min ( $p = 0.01$ , $ES = 20.45$ ) compared with baseline velocity (PAP lost after 12 min recovery).
Cahill, Oliver et al. 2019	N=70, Male Age: 16.7 ± 0.9 years Height: 1.77 ± 0.69m Weight: 75.6 ± 10.9kg Rugby Union Lacrosse	Radar device (Model: Stalker ATS II, Applied Concepts, Dallas, TX, USA)	1 x un-resisted baseline 20m sprint 3x resisted 20m sprint	Vdec of 10, 25, 50, and 75%	Maximum Velocity, Velocity Decrement	L-V relationship were reliable (coefficient of variation (CV) = 3.1%). L-V relationship were highly linear ( $r > 0.95$ ). High between-participant variability (95% confidence intervals) in given Vdec loading, e.g., loads of 14–21%BM causing 10% Vdec, 36–53%BM causing 25% Vdec, 71–107%BM causing 50% Vdec, and 107–160%BM causing 75% Vdec.
** Tierney et al. 2019	N=13, Male Age: 25 ± 3 years Height: 1.86 ± 0.06m Weight: 103.9 ± 10.7kg Rugby Union	Micro-sensor technology units (StatSports Group Limited, Co. Down, Northern Ireland). 10 Hz GPS data (augmented to 18 Hz), accelerometer data at a rate of 600 Hz, magnetometer data at a rate of 10 Hz, and gyroscope data at a rate of 400 Hz.	8 weeks training phase of resisted sled sprint training sessions. Data collected as part of the participant's usual athletic performance training	Baseline- 10 m resisted sprint at a total external resistance of 30 kg, 45 kg, 60 kg, 75 kg (sled and harness mass = 14.8 kg)	Resisted Sled Momentum, BM Momentum, Vmax	Calculation of momentum is an easily applicable and practical method of determining an optimal load during RSS training for improving acceleration and sprint performance.

Zabaloy et al. 2020	N=20, Male Age: 22.5 ± 5.3 years Height: 1.80 ± 0.05m Weight: 80.2 ± 15.2kg Rugby Union	Timing Gates- Photoelectric cells (Microgate, Bolzano, Italy) placed at 1 m height on the start line and at 5, 10, 20, 25, and 30 m. Radar gun (Stalker ATS II, Applied Concepts, Richardson, TX, USA), sampling frequency of 47 Hz and placed 5 m behind the starting line at 1 m height. Linear position transducer (Chronojump, Boscosystem, Barcelona, Spain). Force Plate (Kistler 9286BA, Winterthur, Switzerland) sampling at 350 Hz.	Day 1: 2x 30 m sprints at each different load. Day 2 (72hrs later): CMJ, SJ, and dynamic (i.e., 1RM Squat) and isometric (i.e., squat and SIST) assessments were conducted.	30M Sprints= 0%, 20%, 40%, 60%, and 80% BM, randomly applied. 1RM Strength	Vmax, Vloss, Max Jump Height, Relative Peak Power, Resultant Mean, Force, Mean Propulsive, Velocity	Moderate to strong correlations were found between Vmax, SJ, and CMJ (height), although Vmax was not associated to SIST or SISTrel.
Kawamori et al. 2014	N=10, Male Age: 27.9 ± 1.9 Height: 1.76 ± 0.06m Weight: 80.2 ± 9.6kg Mixed Team Sports (basketball, soccer, rugby, baseball, Australian rules football)	Electronic timing light system with double-beam photocells (Swift Performance Equipment, Lismore, Australia). Force plates at 1000Hz (Type 9287BA, Kistler Instrument Corp., Winterthur, Switzerland, 0.9 m long).	2x 5m sprints at each load with 1.5-2min rest between sprints.	0%, 10%, and 30% BM	Ground Reaction Force, Contact time, Toe Off, Foot Strike, Braking, Propulsive Force	Towing a sled weighing 30% of body mass increased relative net horizontal and propulsive impulse production compared to unresisted sprinting ( $p < 0.05$ ).
Cross, Brughelli et al. 2017	N=12, (Sex not clarified) Age: 27 ± 4 years Height: 1.76 ± 0.08m Weight: 82.5 ± 10.47kg Mixed Sports (Field Sport n=11)	Radar device (Model: Stalker ATS II, Applied Concepts, Dallas, TX, USA) set on a tripod 5m behind the athlete at 1m height. Velocity-time data collected at a rate of 46.9 Hz. Calibrated plates (Model: PL Comp Discs, Eleiko Sport, Halmstad, Sweden).	7x max velocity sprints. Distances set at 45 m for unresisted, 40 m at 20%, 30 m at 40%, 30 m at 60%, 30 m at 80%, 20 m at 100%, and 20 m at 120% BM.	Unresisted, 20%, 40%, 60%, 80%, 100%, and 120% BM	F0, L0, V0, Pmax, Pmax 2, SFv, Fopt, Lopt, and Vopt	Mechanical relationships can be accurately profiled using common sled-training equipment. F-V profiles and optimal loading conditions can be accurately and reliably profiled during multiple over-ground sprints.
Petrakos et al. 2019	N=17, Female Age: 20.5 ± 2.0 years Height: 1.68 ± 0.65m Weight: 64.8 ± 8.7 kg Mixed field sports (field hockey, soccer, Gaelic football)	Infrared, single-beam speed gates (Fusion Sport, Queensland, Australia) were placed at 0, 10, and 20 m, at a height of 1 m.	Repeat resisted sprints until failure at load increments of 0.5-5kg	Initial load of 15%BM	1RM	Maximum resisted sled load was “moderately” and “strongly” correlated with ( $p < 0.05$ ) percentage fat free mass, countermovement jump, loaded countermovement jump, rate of force development, horizontal jump, and horizontal bound performance. MRS� is reliable for determining max acceleration load over 0-20 m.

Cottle et al. 2014	N=17, n=10 Male, n=7 Female Age: 20.9 ± 1.1 years Height: 1.7 ± 0.1m Weight: 62.2 ± 22.1kg Field & Court sports	AMTI BP400600 force plates (AMTI Watertown, MA, USA) set at 2400 Hz. Visual 3D (C-motion, Germantown, MD, USA).	5x approx. 10m sprint trials at each load	0%, 10%, and 20% BM	Ground reaction force, impulse, peak propulsive GRF, rate of force development (RFD)	Propulsive GRF & impulse were greater in 20% BM condition than unweighted in both limbs and 20% BM condition was greater than the 10% BM condition in the front leg only, and vertical GRF impulse was greater in the 20% BM than unweighted. 10% BM load was not sufficient to increase propulsive GRF impulse.
Murray et al. 2005	N=33, Male Age: 21.1 ± 1.8 years Height: 1.82 ± 0.1m Weight: 83.6 ± 13.1kg Rugby Union & Soccer	Timing gates (Brower Timing System, Utah, USA). Video camera (Panasonic, NV-MS5 SVHS Video Camera) placed at a 90-degree angle to the 20 m gate.	2 sets of 7x sprints across 20m	0, 5, 10, 15, 20, 25 and 30% BM.	Stride length, Stride frequency, Sprint time	Statistically significant (but not meaningful) quadratic relationship between sprint time and resistance as sprint time increased from 2.94 s to 3.80 s from 0 to 30%BM resistance. As resistance increased, stride length shortened, there was no change to stride frequency.
**Morin et al. 2017	N=16, Male (n=10 experimental, n=6 control) Age: experimental- 26.3 ± 4.0 years, control- 26.8 ± 4.2 years Height: experimental- 1.77 ± 0.08m, control- 1.75 ± 0.08m Weight: experimental- 74.5 ± 5.3kg, control- 70.7 ± 6.5kg. Soccer	Radar device (Stalker ATS Pro II, Applied Concepts, TX, USA).	16 sprint sessions over 8 weeks. 2 blocks of 5x 20m sprints.	Experimental- 80%BM Control- 0%BM	Velocity, Horizontal GRF, Horizontal power output, Theoretical max velocity and force	Very heavy sled tow increased max horizontal-force production compared with unloaded sprint training (effect size of 0.80 vs 0.20 for controls, unclear between-groups difference) and mechanical effectiveness (i.e., more horizontally applied force; effect size of 0.95 vs -0.11, moderate between-groups difference). 5-m and 20-m sprint performance improvements were moderate and small for the very-heavy sled group and small and trivial for the control group.
**West et al. 2013	N=20, Male (Sled group, or traditional group) Age: SLED-26.8 ± 3.0 years, TRAD-25.1 ± 3.2 years Height: SLED-1.86 ± 0.80m, TRAD- 1.85 ± 0.70m Weight: SLED- 90.2 ± 10.3kg, TRAD- 90.9 ± 10.6kg Rugby Union	Electronic timing gates (Brower TC-System; Brower Timing Systems, Draper, UT, USA), set up at the start line and then 10 and 30m.	12 sessions over 6 weeks. SLED- 3x20m resisted sprint TRAD-3x20m unresisted sprint (Pre and Post test of 10 and 30m)	SLED- 12.6% BM TRAD- unresisted sprint	Velocity	Both training programmes improved participants' 10 and 30 m speed ( $p < 0.001$ ), but pre to post testing in 10 m ( $p < 0.001$ ) and 30 m ( $p < 0.003$ ) sprint times were significantly greater in the SLED training group. Similarly, the percent change within the SLED group for the 10 m ( $p < 0.003$ ) and 30 m ( $p < 0.003$ ) tests were greater than the TRAD group.

<p>**Cross, Lahti et al. 2018</p>	<p>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 &amp; Soccer</p>	<p>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.</p>	<p>12 sessions of 10 × 20m and pre/post-profiling, at 10% decrement in individual maximum velocity, or at individualised optimal loading for maximal power.</p>	<p>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).</p>	<p>Velocity Horizontal power Maximum theoretical velocity and force</p>	<p>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.</p>
-----------------------------------	--	---	---	---	---	--

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  $\leq 10\%$ BM had minimal effects on GRF (Cottle et al., 2014; Kawamori et al., 2014). Moreover, sled loads of  $\leq 10\%$ 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  $\leq 5\%$ ) (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.

## Acknowledgment

This review is non-funded.

## References

- Alcaraz, P. E., Elvira, J. L. L., & Palao, J. M. (2012). Kinematic, strength, and stiffness adaptations after a short-term sled towing training in athletes. *Scandinavian Journal of Medicine & Science in Sports*, 24(2), 279–290. <https://doi.org/10.1111/j.1600-0838.2012.01488.x>
- Alcaraz, P. E., Carlos-Vivas, J., Oponjuru, B. O., & Martínez-Rodríguez, A. (2018). The effectiveness of resisted sled training (RST) for sprint performance: A systematic review and meta-analysis. *Sports Medicine*, 48(9), 2143–2165. <https://doi.org/10.1007/s40279-018-0947-8>
- Altmann, S., Spielmann, M., Engel, F. A., Neumann, R., Ringhof, S., Oriwol, D., & Haertel, S. (2017). Validity of single-beam timing lights at different heights. *Journal of Strength and Conditioning Research*, 31(7), 1994–1999. <https://doi.org/10.1519/jsc.0000000000001889>
- Altmann, S., Spielmann, M., Engel, F. A., Ringhof, S., Oriwol, D., Härtel, S., & Neumann, R. (2018). Accuracy of single beam timing lights for determining velocities in a flying 20-m

- sprint: Does timing light height matter? *Journal of Human Sport and Exercise*, 13(3), 601-610. <https://doi.org/10.14198/jhse.2018.133.10>
- Andre, M. J., Fry, A. C., Bradford, L. A., & Buhr, K. W. (2013). Determination of friction and pulling forces during a weighted sled pull. *Journal of Strength and Conditioning Research*, 27(5), 1175–1178. <https://doi.org/10.1519/jsc.0b013e318269aaef>
- Bentley, I., Atkins, S. J., Edmundson, C. J., Metcalfe, J., & Sinclair, J. K. (2016). Impact of harness attachment point on kinetics and kinematics during sled towing. *Journal of Strength and Conditioning Research*, 30(3), 768–776. <https://doi.org/10.1519/jsc.0000000000001155>
- Bond, C. W., Willaert, E. M., & Noonan, B. C. (2017). Comparison of three timing systems: Reliability and best practice recommendations in timing short-duration sprints. *Journal of Strength and Conditioning Research*, 31(4), 1062–1071. <https://doi.org/10.1519/jsc.0000000000001566>
- Cahill, M. J., Cronin, J. B., Oliver, J. L., P. Clark, K., Lloyd, R. S., & Cross, M. R. (2019). Sled pushing and pulling to enhance speed capability. *Strength & Conditioning Journal*, 41(4), 94–104. <https://doi.org/10.1519/ssc.0000000000000460>
- Cahill, M. J., Oliver, J. L., Cronin, J. B., Clark, K. P., Cross, M. R., & Lloyd, R. S. (2019). Sled-pull load–velocity profiling and implications for sprint training prescription in young male athletes. *Sports*, 7(5), 119. <https://doi.org/10.3390/sports7050119>
- Carlos-Vivas, J., Marín-Cascales, E., Freitas, T. T., Perez-Gomez, J., & Alcaraz, P. E. (2019). Force-velocity-power profiling during weighted-vest sprinting in soccer. *International Journal of Sports Physiology and Performance*, 14(6), 747–756. <https://doi.org/10.1123/ijsp.2018-0490>
- Carlos-Vivas, J., Perez-Gomez, J., Eriksrud, O., Freitas, T. T., Marín-Cascales, E., & Alcaraz, P. E. (2020). Vertical versus horizontal resisted sprint training applied to young soccer players: Effects on physical performance. *International Journal of Sports Physiology and Performance*, 15(5), 748–758. <https://doi.org/10.1123/ijsp.2019-0355>
- Challis, J. H. (2001). The variability in running gait caused by force plate targeting. *Journal of Applied Biomechanics*, 17(1), 77–83. <https://doi.org/10.1123/jab.17.1.77>
- Clark, K. P., Stearne, D. J., Walts, C. T., & Miller, A. D. (2010). The longitudinal effects of resisted sprint training using weighted sleds vs. weighted vests. *Journal of Strength and Conditioning Research*, 24(12), 3287–3295. <https://doi.org/10.1519/jsc.0b013e3181b62c0a>
- Cochrane, D. J., & Monaghan, D. (2021). Using sprint velocity decrement to enhance acute sprint performance. *Journal of Strength and Conditioning Research*, 35(2), 442–448. <https://doi.org/10.1519/jsc.0000000000002707>
- Cottle, C. A., Carlson, L. A., & Lawrence, M. A. (2014). Effects of sled towing on sprint starts. *Journal of Strength and Conditioning Research*, 28(5), 1241–1245. <https://doi.org/10.1519/jsc.0000000000000396>
- Cronin, J. B., & Templeton, R. L. (2008). Timing light height affects sprint times. *Journal of Strength and Conditioning Research*, 22(1), 318–320. <https://doi.org/10.1519/jsc.0b013e31815fa3d3>
- Cross, M. R., Brughelli, M., Samozino, P., Brown, S. R., & Morin, J.-B. (2017). Optimal loading for maximizing power during sled-resisted sprinting. *International Journal of Sports Physiology and Performance*, 12(8), 1069–1077. <https://doi.org/10.1123/ijsp.2016-0362>
- Cross, M. R., Brughelli, M., Samozino, P., & Morin, J.-B. (2016). Methods of power-force-velocity profiling during sprint running: A narrative review. *Sports Medicine*, 47(7), 1255–1269. <https://doi.org/10.1007/s40279-016-0653-3>
- Cross, M. R., Lahti, J., Brown, S. R., Chedati, M., Jimenez-Reyes, P., Samozino, P., ... Morin, J.-B. (2018). Training at maximal power in resisted sprinting: Optimal load determination methodology and pilot results in team sport athletes. *PLOS ONE*, 13(4), e0195477. <https://doi.org/10.1371/journal.pone.0195477>
- Cross, M. R., Samozino, P., Brown, S. R., & Morin, J.-B. (2018). A comparison between the force–velocity relationships of unloaded and sled-resisted sprinting: Single vs. multiple trial methods. *European Journal of Applied Physiology*, 118(3), 563–571. <https://doi.org/10.1007/s00421-017-3796-5>
- Cross, M. R., Tinwala, F., Lenetsky, S., Samozino, P., Brughelli, M., & Morin, J.-B. (2016). Determining friction and effective loading for sled sprinting. *Journal of Sports Sciences*, 35(22), 2198–2203. <https://doi.org/10.1080/02640414.2016.1261178>
- Debaere, S., Jonkers, I., & Delecluse, C. (2013). The contribution of step characteristics to sprint running performance in high-level male and female athletes. *Journal of Strength and Conditioning Research*, 27(1), 116–124. <https://doi.org/10.1519/jsc.0b013e31825183ef>
- Earp, J. E., & Newton, R. U. (2012). Advances in electronic timing systems. *Journal of Strength and Conditioning Research*, 26(5), 1245–1248. <https://doi.org/10.1519/jsc.0b013e3182474436>
- Exell, T. A., Gittoes, M. J. R., Irwin, G., & Kerwin, D. G. (2012). Considerations of force plate transitions on centre of pressure calculation for maximal velocity sprint running. *Sports Biomechanics*, 11(4), 532–541. <https://doi.org/10.1080/14763141.2012.684698>
- Ferro, A., Floría, P., Villaceros, J., & Aguado-Gómez, R. (2012). Validity and reliability of the laser sensor of BioLaserSport® system for the analysis of the running velocity. *The International Journal of Medicine and Science in Physical Education and Sport*, 8, 357–370.
- Gil, S., Barroso, R., Crivoi do Carmo, E., Loturco, I., Kobal, R., Tricoli, V., ... Roschel, H. (2018). Effects of resisted sprint training on sprinting ability and change of direction speed in professional soccer players. *Journal of Sports Sciences*, 36(17), 1923–1929. <https://doi.org/10.1080/02640414.2018.1426346>
- Haugen, T. A., Tønnessen, E., Svendsen, I. S., & Seiler, S. (2014). Sprint time differences between single- and dual-beam timing systems. *Journal of Strength and Conditioning Research*, 28(8), 2376–2379. <https://doi.org/10.1519/jsc.0000000000000415>
- Haugen, T., & Buchheit, M. (2015). Sprint running performance monitoring: Methodological and practical considerations.

- Sports Medicine*, 46(5), 641–656.  
<https://doi.org/10.1007/s40279-015-0446-0>
- Johnston, R. J., Watsford, M. L., Pine, M. J., Spurrs, R. W., Murphy, A. J., & Pruyn, E. C. (2012). The validity and reliability of 5-hz global positioning system units to measure team sport movement demands. *Journal of Strength and Conditioning Research*, 26(3), 758–765.  
<https://doi.org/10.1519/jsc.0b013e318225f161>
- Kawamori, N., Newton, R., & Nosaka, K. (2014). Effects of weighted sled towing on ground reaction force during the acceleration phase of sprint running. *Journal of Sports Sciences*, 32(12), 1139–1145.  
<https://doi.org/10.1080/02640414.2014.886129>
- Lacome, M., Peeters, A., Mathieu, B., Bruno, M., Christopher, C., & Piscione, J. (2019). Can we use GPS for assessing sprinting performance in rugby sevens? A concurrent validity and between-device reliability study. *Biology of Sport*, 36(1), 25–29. <https://doi.org/10.5114/biolsport.2018.78903>
- Letzelter, M., Sauerwein, G., & Burger, R. (1995). Resistance runs in speed development. *Modern Athlete and Coach*, 33, 7–12.
- Linthorne, N. P., & Cooper, J. E. (2013). Effect of the coefficient of friction of a running surface on sprint time in a sled-towing exercise. *Sports Biomechanics*, 12(2), 175–185.  
<https://doi.org/10.1080/14763141.2012.726638>
- Loturco, I., Pereira, L., Kopal, R., Cal Abad, C., Fernandes, V., Ramirez-Campillo, R., & Suchomel, T. (2018). Portable force plates: A viable and practical alternative to rapidly and accurately monitor elite sprint performance. *Sports*, 6(3), 61.  
<https://doi.org/10.3390/sports6030061>
- Macadam, P., Simperingham, K. D., & Cronin, J. B. (2017). Acute kinematic and kinetic adaptations to wearable resistance during sprint acceleration. *Journal of Strength and Conditioning Research*, 31(5), 1297–1304.  
<https://doi.org/10.1519/jsc.0000000000001596>
- Maulder, P. S., Bradshaw, E. J., & Keogh, J. W. (2008). Kinematic alterations due to different loading schemes in early acceleration sprint performance from starting blocks. *Journal of Strength and Conditioning Research*, 22(6), 1992–2002.  
<https://doi.org/10.1519/jsc.0b013e31818746fe>
- McMaster, D. T., Gill, N., Cronin, J., & McGuigan, M. (2013). The development, retention and decay rates of strength and power in Elite Rugby Union, Rugby League and American Football. *Sports Medicine*, 43(5), 367–384.  
<https://doi.org/10.1007/s40279-013-0031-3>
- Moher, D., Liberati, A., Tetzlaff, J., & Altman, D. G. (2009). Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. *BMJ*, 339, b2535.  
<https://doi.org/10.1136/bmj.b2535>
- Monte, A., Nardello, F., & Zamparo, P. (2017). Sled towing: The optimal overload for peak power production. *International Journal of Sports Physiology and Performance*, 12(8), 1052–1058.  
<https://doi.org/10.1123/ijsp.2016-0602>
- Morin, J.-B., Petrakos, G., Jiménez-Reyes, P., Brown, S. R., Samozino, P., & Cross, M. R. (2017). Very-Heavy sled training for improving horizontal-force output in soccer players. *International Journal of Sports Physiology and Performance*, 12(6), 840–844.  
<https://doi.org/10.1123/ijsp.2016-0444>
- Murray, A., Aitchison, T., Ross, G., Sutherland, K., Watt, I., McLean, D., & Grant, S. (2005). The effect of towing a range of relative resistances on sprint performance. *Journal of Sports Sciences*, 23(9), 927–935.  
<https://doi.org/10.1080/02640410400023332>
- Pantoja, P. D., Carvalho, A. R., Ribas, L. R., & Peyré-Tartaruga, L. A. (2018). Effect of weighted sled towing on sprinting effectiveness, power and force-velocity relationship. *PLOS ONE*, 13(10), e0204473.  
<https://doi.org/10.1371/journal.pone.0204473>
- Peterson Silveira, R., Stergiou, P., Carpes, F. P., Castro, F. A. de S., Katz, L., & Stefanyshyn, D. J. (2016). Validity of a portable force platform for assessing biomechanical parameters in three different tasks. *Sports Biomechanics*, 16(2), 177–186.  
<https://doi.org/10.1080/14763141.2016.1213875>
- Petrakos, G., Morin, J.-B., & Egan, B. (2015). Resisted sled sprint training to improve sprint performance: A systematic review. *Sports Medicine*, 46(3), 381–400.  
<https://doi.org/10.1007/s40279-015-0422-8>
- Petrakos, G., Tynan, N. C., Valley-Farrell, A. M., Kiely, C., Boudhar, A., & Egan, B. (2019). Reliability of the maximal resisted sprint load test and relationships with performance measures and anthropometric profile in female field sport athletes. *Journal of Strength and Conditioning Research*, 33(6), 1703–1713.  
<https://doi.org/10.1519/jsc.0000000000002228>
- Rabita, G., Dorel, S., Slawinski, J., Sàez-de-Villarreal, E., Couturier, A., Samozino, P., & Morin, J.-B. (2015). Sprint mechanics in world-class athletes: A new insight into the limits of human locomotion. *Scandinavian Journal of Medicine & Science in Sports*, 25(5), 583–594.  
<https://doi.org/10.1111/sms.12389>
- Roe, G., Darrall-Jones, J., Black, C., Shaw, W., Till, K., & Jones, B. (2017). Validity of 10-HZ GPS and timing gates for assessing maximum velocity in professional rugby union players. *International Journal of Sports Physiology and Performance*, 12(6), 836–839.  
<https://doi.org/10.1123/ijsp.2016-0256>
- Samozino, P., Rabita, G., Dorel, S., Slawinski, J., Peyrot, N., Saez de Villarreal, E., & Morin, J.-B. (2015). A simple method for measuring power, force, velocity properties, and mechanical effectiveness in sprint running. *Scandinavian Journal of Medicine & Science in Sports*, 26(6), 648–658.  
<https://doi.org/10.1111/sms.12490>
- Simperingham, Kim D., Cronin, J. B., & Ross, A. (2016). Advances in sprint acceleration profiling for field-based team-sport athletes: Utility, reliability, validity and limitations. *Sports Medicine*, 46(11), 1619–1645.  
<https://doi.org/10.1007/s40279-016-0508-y>
- Simperingham, Kim David, Cronin, J. B., Pearson, S. N., & Ross, A. (2017). Reliability of horizontal force–velocity–power profiling during short sprint-running accelerations using radar technology. *Sports Biomechanics*, 18(1), 88–99.  
<https://doi.org/10.1080/14763141.2017.1386707>

- Tierney, P., Reardon, C., & Delahunt, E. (2019). Momentum: a practical solution to calculate the optimal load for resisted sled sprint training. *Sport Performance & Science Reports*, 1(68), 1–5.
- Van Den Tillaar, R., Teixeira, A., & Marinho, D. (2018). Acute effect of resisted sprinting upon regular sprint performance. *Acta Kinesiologiae Universitatis Tartuensis*, 23, 19-33. <https://doi.org/10.12697/akut.2017.23.02>
- Varley, M. C., Fairweather, I. H., & Aughey, R. J. (2012). Validity and reliability of GPS for measuring instantaneous velocity during acceleration, deceleration, and constant motion. *Journal of Sports Sciences*, 30(2), 121–127. <https://doi.org/10.1080/02640414.2011.627941>
- West, D. J., Cunningham, D. J., Bracken, R. M., Bevan, H. R., Crewther, B. T., Cook, C. J., & Kilduff, L. P. (2013). Effects of resisted sprint training on acceleration in professional rugby union players. *Journal of Strength and Conditioning Research*, 27(4), 1014–1018. <https://doi.org/10.1519/jsc.0b013e3182606cff>
- Young, W., Benton, D., & Pryor, J. (2001). Resistance training for short sprints and maximum-speed sprints. *Strength and Conditioning Journal*, 23(2), 7. <https://doi.org/10.1519/00126548-200104000-00001>
- Zabaloy, S., Carlos-Vivas, J., Freitas, T. T., Pareja-Blanco, F., Pereira, L., Loturco, I., ... Alcaraz, P. E. (2020). Relationships between resisted sprint performance and different strength and power measures in rugby players. *Sports*, 8(3), 34. <https://doi.org/10.3390/sports8030034>

## Exploring how the experiences of English youth football coaches have shaped their approach to player learning

Sean Jewell<sup>1</sup>, Colm P. Murphy<sup>2</sup>, Chris Pocock<sup>3</sup>, Jamie S. North<sup>1\*</sup>

<sup>1</sup>Faculty of Sport, Allied Health and Performance Science, St Mary's University, Twickenham, UK

<sup>2</sup>Cardiff School of Sport and Health Sciences, Cardiff Metropolitan University, Cardiff, UK

<sup>3</sup>Institute of Sport, Nursing and Allied Health, University of Chichester, UK

### ARTICLE INFO

Received: 30.03.2021

Accepted: 01.09.2022

Online: 23.09.2022

#### Keywords:

Coach Education

Skill Acquisition

Ecological Dynamics

### ABSTRACT

Recently the Football Association (FA) has highlighted a need to move away from traditional approaches to player learning through the dissemination of contemporary pedagogical research. Researchers have attempted to evaluate this process by investigating the practice activities engaged in by youth football teams; however, there remains limited understanding of why coaches adopt certain approaches to player learning. By acquiring youth football coaches' insights, this study addressed this gap by giving coaches a platform to share their approaches to player learning and the different experiences that have shaped it. Eight English youth football coaches (minimum FA Level 2 coaching qualification) were interviewed. Using inductive thematic analysis, eight higher order themes were identified and organised into three dimensions: (i) approaches to player learning, (ii) the coaching environment, and (iii) opportunities for learning and development. Despite some contemporary skill acquisition principles being evident in player learning approaches, coaches' understanding of how specific practice activities impact player learning outcomes was somewhat limited. Learning approaches themselves were not static, but dynamic and adaptable depending on social and contextual factors within the coaching environment. Similarly, these approaches were informed by a multitude of formal and informal learning opportunities, not solely formal coach education pathways. Together, the findings present a challenge for coach educators to account for the individual requirements of coaches and highlight the need to disseminate contemporary pedagogical principles in an easily digestible, transferable, and practical manner.

## 1. Introduction

Youth coaches are integral to helping athletes acquire the necessary skills to perform successfully in competitive sports such as football (Ford, Yates, & Williams, 2010). The approaches taken by youth coaches can shape learning environments, meaning they occupy a position of centrality and influence in the learning, growth, and achievement of aspiring young players (Cushion, 2013; Ford et al., 2010; Partington & Cushion, 2013). Consequently, it is important to develop coaches with the expertise to create learning environments that can best support effective skill acquisition and skill adaptation of players under their tutelage (Wright & Kim, 2019).

In the UK, coach development has been spearheaded by the UK Coaching Framework, which has encouraged the adoption of evidenced-based coaching practises to help improve the quality of the sporting experience for youth athletes (Duffy et al., 2011; Piggott, 2015; Sports Coach UK, 2008). The principles of the UK coaching framework have formed the foundation of the Football Association's (FA) revised coaching strategy, which has aimed to develop existing coaching methods within English football by disseminating high-quality pedagogical research that can be practically applied across the whole game (Allison, 2016). At the core of this, a dynamic and constantly evolving philosophy known as the 'England DNA' was introduced (Ashworth, 2014; FA Education, 2015). The England DNA highlights the need for the

\*Corresponding Author: Jamie S. North, Faculty of Sport, Allied Health and Performance Science, St Mary's University, UK, [jamie.north@stmarys.ac.uk](mailto:jamie.north@stmarys.ac.uk),

<http://orcid.org/0000-0003-2429-4552>

development of a coherent identity within English football, placing both how players play (i.e., technical and tactical skills), and how they are coached (i.e., coaching methodologies and the delivery of training), at the centre of it (Ashworth, 2014). It is clear that from the top down, the need to provide access to high quality evidenced-based coaching methods is fundamental to the FA's vision for developing players and coaches alike, and ultimately moving away from traditional pedagogical techniques that have been said to characterise typical coaching practice (Alisson, 2016).

Traditionally, player development has been considered a 'coach-centred' process, which has been suggested to have hindered the integration of innovative and progressive coaching methods within English football (Cushion & Jones, 2006; North, 2016). As a result, traditional pedagogies, characterised by high levels of instruction, corrective feedback, and repetitive attempts to reproduce coach prescribed skills, have become a common feature of coaching practice (Cushion, 2013; Davids, Gullich, Shuttleworth, & Araújo, 2017; Ford et al., 2010; Partington & Cushion, 2013). However, such an approach is thought to undermine the technical and tactical development of English players (Cushion, Ford, & Williams, 2012).

Typically, traditional coaching pedagogies take a 'process-product' approach to player learning, where the mastery of isolated coach-prescribed skills is emphasised (Cassidy, Jones, & Potrac, 2009; Harvey, Cushion, & Massa-Gonzalez, 2010; Partington & Cushion, 2013). Yet performing successfully in sports such as football presents the learner with considerably more challenge than repeating simple putative actions (Chow, Shuttleworth, Davids, & Araújo, 2019; Ford & Williams, 2013). For example, the execution of a 20-yard pass requires interpretation of dynamic patterns of play, awareness of positional features on the pitch, quick and appropriate decision making, and skill execution with effective technique. As traditional pedagogical methods look to teach skills through practises void of these representative demands, they are often observed to be associated with limited ability to problem solve independently, low levels of transfer to competitive environments, and poor performance in pressurised situations (Chow et al., 2019; Davids, Button, & Bennett, 2008; Masters, Van Duijn, & Uiga, 2019; Williams & Hodges, 2005). Therefore, it has been argued that practice should encourage the learner to explore and develop functional movement strategies in response to the demands of gameplay (Chow, Davids, Button, & Renshaw, 2016; Davids et al., 2014; Moy, Renshaw, Davids, & Brymer, 2016).

Alternative pedagogical approaches to skill acquisition (e.g., the Constraints-Led Approach, see Renshaw, Headrick, Maloney, Moy, & Pinder, 2019; Non-Linear Pedagogy, see Chow, 2013) conceptualise performers as complex adaptive systems. Guided by the framework of ecological dynamics, these approaches propose that the learner's capacity to adapt to the interacting individual, task, and environmental constraints on performance will determine the behaviours that emerge (Araújo & Davids, 2011; Davids, Araújo, Seifert, & Orth, 2015; Pinder, Davids, Renshaw, & Araújo, 2011). Accordingly, the successful acquisition of skills involves the development of a functional performer-environment relationship, whereby the learner can develop functional movement strategies in response to the acting constraints on performance (Araújo, Davids, Chow, Passos, & Raab, 2009; Davids, Araújo, Correia, & Vilar, 2012).

From an ecological dynamics perspective, there are several important principles that serve to enhance the acquisition of skills. Fundamentally, information that is accessible when learning a skill should be relevant to what is available in the performance environment (Chow et al., 2016). As information informs action in a dynamic, cyclical manner, the accessibility of 'specifying' or high-quality information when learning a skill is considered essential to the development of facilitative information-movement couplings, which players can use to achieve performance goals (Chow et al., 2019). In football, small-sided and conditioned games (SSGs) can encourage learners to execute skills in the presence of specifying information (e.g., the movement of teammates or presence of defenders), presenting the learner with a multitude of affordances (opportunities for action) that are representative of those in the performance environment (Davids, Araújo, Hristovski, Passos, & Chow, 2012; Davids et al., 2013; Pinder et al., 2011). Consequently, the information-movement couplings that are developed are more likely to lead to efficient transfer of skills from training to matches (Davids et al., 2013; Travassos, Duarte, Vilar, Davids, & Araújo, 2012; Woods, McKeown, O'Sullivan, Robertson, & Davids, 2020).

Using the framework of ecological dynamics, creating environments that encourage players to practice skills under representative conditions should be at the forefront of the coaches' theoretical approach (Davids et al., 2013; Pocock, Bezodis, Wadey, & North, 2020; Travassos et al., 2012). However, despite these approaches to skill acquisition becoming more prominent in academic research, their uptake by sports coaches appears to remain limited (Jones, Morgan, & Harris, 2012; Renshaw, Davids, Newcombe, & Roberts, 2019). As such, it is important to consider how successfully this information is being applied within English football specifically (Griffiths, Armour, & De Lyon, 2016).

Researchers have investigated this through systematic observation of the practice activities and coaching behaviours employed in youth football (Ford & Whelan, 2016; Partington & Cushion, 2013). It has been reported that youth footballers spend long periods of time in drill-based (or 'training form') activities, where skills are practised in isolation and decision making is prescribed by the coach (Ford et al., 2010; Partington & Cushion, 2013). As drill-based activities do not accurately sample the key specifying information available in the performance environment, the acquisition and transfer of skills is limited as relevant information-movement couplings between key sources of information and action are unavailable (Chow et al., 2019; Pinder et al., 2011). More recently, Ford and Whelan (2016) found a higher proportion of games-based activities were used during youth coaching sessions compared to those reported previously (Ford et al., 2010; Partington & Cushion, 2013). Although this demonstrates increased use of game-based activities, the actual time players spent in these was only 60% of the total session time. Similar observations have been made in the most recent investigation of practice activity in English youth football, which showed the time players spent engaged in representative activity to be 56% of the total session (Roca & Ford, 2020). This suggests that any increases in time spent in representative practice activities have somewhat plateaued.

Striving for sessions consisting solely of games-based activity may be unrealistic for coaches; yet youth coaches in Spain and Portugal have been shown to utilise 10% to 12% more of the session for such activities (Roca & Ford, 2020). Despite a clear

shift in intent (e.g., towards sessions containing a greater proportion of representative games-based activity), English youth football coaches appear to be encountering difficulties in utilising these methods to the extent observed in other countries. Indeed, researchers working with coaches across multiple sports have highlighted that contemporary pedagogical approaches can be challenging to implement (Butler, 2020; Moy et al., 2016; Rothwell, Stone, & David, 2019; Stone, Rothwell, & Shuttleworth, 2020). This is something that can be compounded by a lack of readily available resources to guide practice design (Stone et al., 2020) and the establishment of traditional pedagogical coaching cultures (Ross, Gupta, & Sanders, 2018).

With the FA continuing to focus on reforming England’s approach to youth coaching (Griffiths et al., 2016), it is important that researchers evaluate its success to ensure coaching and coach education processes are evidence-based (Ford & Whelan, 2016). By acquiring coaches’ experiential knowledge, this study aimed to further current understanding of *what* youth football coaches are doing (e.g., session structure and practice activities), as well as providing a platform for youth football coaches to share *why* they design practice in such a way, and how different experiences have influenced their approach. The insights gained may help to establish how successful the transfer of pedagogical evidence into applied practice has been by: (i) highlighting approaches to player learning across different performance contexts (e.g., grassroots and academy level), (ii) exploring how different coaching environments affect approaches to player learning, and (iii) discussing how influential FA education has been in the development of this approach when compared to other developmental and educational experiences.

## 2. Methods

### 2.1. Participants

Criterion-based purposeful sampling was used to identify individuals with the necessary experience and qualifications to participate. To be included in the study, two key criteria had to be satisfied: current employment as coach of a youth football team or academy, and a minimum of FA level 2 coaching qualification. Eight male youth football coaches that met these criteria were selected and provided written informed consent to participate in

the study ( $M_{age} = 31$  years,  $SD = 8.58$  years;  $M_{experience} = 11$  years,  $SD = 6.48$  years; see Table 1). To maintain anonymity of participants, the specific club or organisation they worked for is not outlined and pseudonyms (e.g., Coach 1, Coach 2 etc.) were provided. Ethical approval was obtained from the lead author’s University ethics committee.

### 2.2. Procedure

Individual interviews were carried out with each participant via internet telephony. A novel semi-structured interview guide (see supplementary information) was used to facilitate each interview. Development of the guide was informed by: (i) relevant theoretical understanding of contemporary learning theories and the organisation of practice activity in youth football (e.g., Davids et al., 2017; Roca & Ford, 2020) (ii) research into the FA’s current approach to coach education (Allison, 2016; Griffiths et al., 2016), (iii) previous investigations into the experiential knowledge of sports coaches (Pocock et al., 2020, Stone et al., 2020), and (iv) the author’s experience of applied coaching practice.

The interview guide was split into three main sections, comprising of: career history, applied practice, and coach development and learning. The aim of each section was to gain an understanding of different aspects of the coach’s career and discuss sources or experiences that have informed their practice. To assess how successful the interview guide was in achieving this, pilot interviews were run with a separate sample of two participants that had experience in coaching youth football. Following these interviews, minor modifications were made concerning the specificity of questions into the coach’s organisation and practice set-up, as both interviewees highlighted that recounting precise practice techniques was challenging. Each interview was audio recorded and transcribed verbatim for later analysis.

### 2.3. Data Analysis

Interviews ranged from 35 minutes to 55 minutes in duration ( $M = 41$  minutes,  $SD = 8$  minutes). To analyse the data, thematic analysis was selected due to its suitability for extracting rich descriptive accounts and identifying common themes across cases (Braun & Clare, 2006; Braun, Clarke, & Weate, 2016). Accepting

Table 1: Participant characteristics for the eight coaches.

Coach	Age	Years Coaching Experience	Highest Coaching Qualification
1	23	7	FA Level 2
2	43	22	UEFA B
3	23	5	FA Level 2
4	23	3	FA Level 2
5	33	15	FA Level 2
6	42	10	FA Level 2
7	23	8	UEFA B
8	39	18	UEFA A

that the experiences of the coaches could differ significantly from one another, an inductive approach was taken. In line with Braun and Clarke's (2006) framework for conducting thematic analysis the first stage of this approach involved the lead author becoming familiar with the transcripts, before working systematically through the data set to generate initial codes. These codes were then sorted into potential themes and represented visually in the form of a thematic map, which encouraged the lead author to think vertically and horizontally about the data (Clarke, Hayfield, Moller, & Tischner, 2017). Following this, the themes were reviewed and refined by the lead researcher before being presented to the co-authors, who acted as critical friends by questioning and challenging the suitability of the derived themes. Once a consensus was reached on the accuracy with which the themes represented the data, the themes were defined and named.

#### 2.4. Methodological Rigor

Methodological rigour was conceptualised from a relativist position meaning techniques specific to the project's aims and design were chosen (Smith & McGannon, 2018, Sparkes & Smith, 2009). First, purposeful sampling with specific criteria (e.g., current employment and coaching qualifications) was used to ensure participants had sufficient experience to fully satisfy the research question (Patton, 2002). Accepting that the lead author's experiences of youth football coaching were inextricably linked to the research process and interpretation of the data, the co-authors also acted as critical friends by encouraging reflexivity about the lead author's own biases for conducting the research (i.e., as a practising youth football coach) and alternative explanations of the findings (Sparkes & Smith, 2009). Although the prior experiences of working in youth football are undoubtedly tied to the research project, it is hoped that the lead author's knowledge of skill acquisition, representative design, and applied coaching practice has served to enrich the interpretation of findings rather than compromising them (Weed, 2009). The authors have attempted to demonstrate sincerity by acknowledging, accepting and being transparent about *a priori* knowledge of the subject area (Tracey, 2010). Member reflections were carried out with three of the participants, providing a practical opportunity to explore any differences concerning the researcher's interpretation of the results (Schinke, Smith, & McGannon, 2013). These involved participants being sent a copy of their transcript and summary of the results, before being given an opportunity to feedback on any similarities or contradictions they had with the findings. No changes were made following these reflections.

### 3. Results and Discussion

Inductive analysis of the data identified 8 higher order themes (Figure 1), which were categorised into 3 dimensions: approaches to player learning, the coaching environment, and opportunities for learning and development. These dimensions reflected the aims of the study by first presenting coaches' approaches to player learning within the context of contemporary pedagogical evidence, before considering the range of experiences that shape this approach. The three dimensions are discussed as separate

subsections, with key quotes from the coaches used to illustrate each of the higher order themes.

#### 3.1. Approaches to Player Learning

Within this dimension, coaches' views on their approaches to player learning are presented. Two higher order themes of traditional and contemporary methods, specifically related to skill acquisition principles, were identified.

##### 3.1.1. Traditional Methods

In line with previous research (e.g., Williams, Alder, & Bush, 2015), traditional pedagogical approaches were still common within coaching practice. This was evidenced through coaches' desire to teach fundamental movements and skills through isolated, technical drills. The coaches interviewed in this study reported that technical drills often form an introductory activity to progress from when looking to practice specific skills or themes during a session:

"My session will always be a basic warm-up with lots of movement and unopposed ball work, then 15-20 minutes of technical work, before taking that into a tactical practice and ending with a small-sided game" (Coach 5).

This highlights how coaches look to build their session from simplistic fundamental movements and skills, before integrating tactical information or games-based methods. Adopting a less dichotomous approach that facilitates the development of technique under conditions representative of actual gameplay would be more effective in promoting efficient transfer of these technical skills, whilst also encouraging the development of fundamental game skills (e.g., decision making and anticipation) (Miller, Harvey, & Morley, 2017; Roca, Ford, & McRobert, 2011, Smith, 2016). However, coaches believed that technical drills provided an opportunity to repeat and refine skills that could be transferred into game situations:

"I'll do a passing rotation... and what you're looking at is the details, movement in and out to receive, checking your shoulder. I know every time I'm passing to the same place, but I'm repeating and repeating it because when we go into possession or games you are then in the habit of making those movements" (Coach 7).

Despite this belief, drill-based activities can fail to accurately sample key specifying information available in the performance environment and constrain the decision-making processes of the learner (Chow et al., 2016; Ford & Williams, 2013). Consequently, the transfer of skills is likely to be limited (Chow et al., 2019; Roca, Ford, & McRobert, 2013). Whilst the acquisition of technical skills may be important (Smith, 2016), and research is emerging to highlight potential motivational benefits of practising under less challenging conditions (Hodges & Lohse, 2022), it is important that skills are not taught using only non-representative tasks to ensure coaches do not risk limiting the development of their players, and transfer of skills to competitive environments (Cushion et al., 2012; Pinder et al., 2011). As is

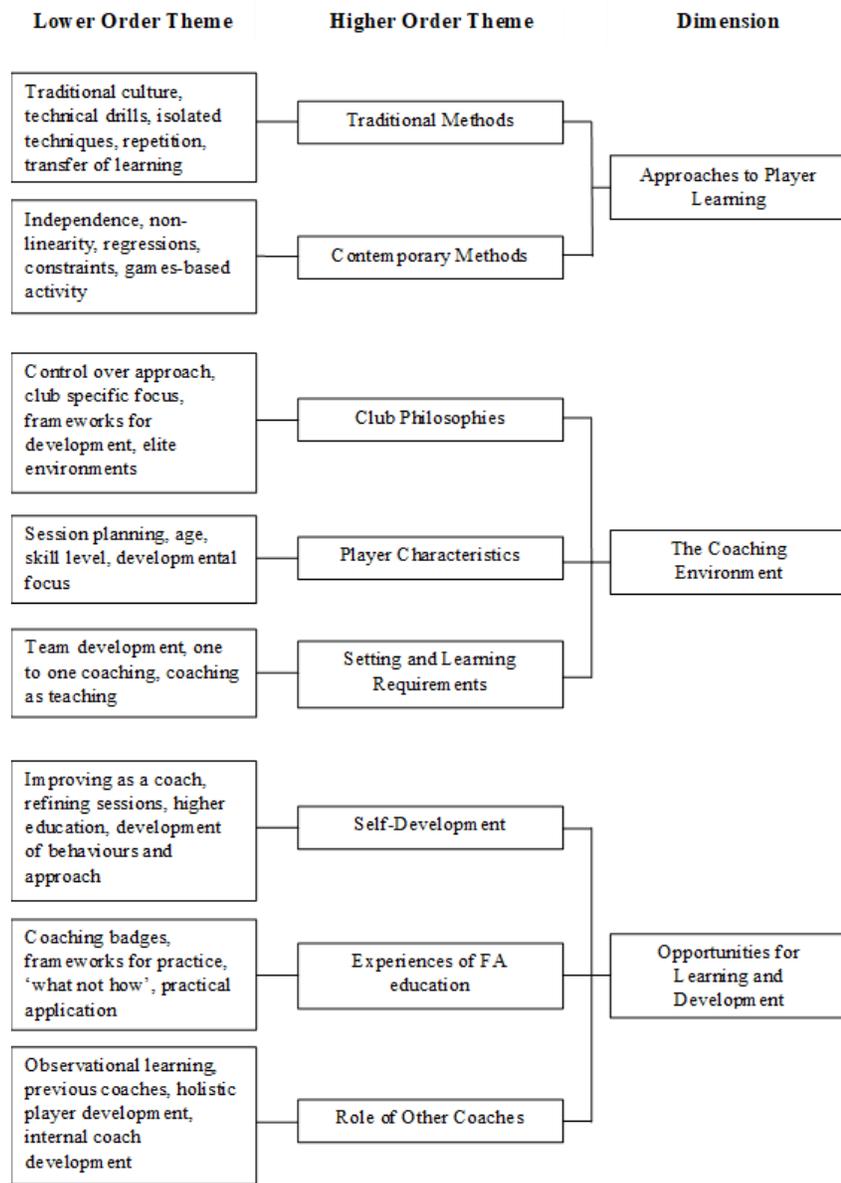


Figure 1: Thematic map displaying the lower order themes, higher order themes, and dimensions of the data set.

presented and discussed in the following theme, coaches do not tend to operate solely within either a ‘traditional’ or ‘contemporary’ framework, however the types of activity employed remain fairly distinct within their sessions. Perhaps most important therefore is looking to address the epistemological gap in coaches’ understanding of the relationship between practice activities and player learning outcomes. Coach educators must continue to prioritise education of youth football coaches about what representative practice looks like and why it is important, providing practical resources for how to implement these methods into progressive, technically focused sessions (Ford & Whelan, 2016; Moy et al., 2016; Partington & Cushion, 2013; Stone et al., 2020). This process must be supported by ongoing research that not only provides recommendations for

practice, but also meaningful and digestible frameworks to implement key learning principles (Woods, McKeown, & O’ Sullivan, 2020).

### 3.1.2. Contemporary Methods

The coaches highlighted how they used a range of contemporary learning principles within their practice. For the most part these were not explicitly referenced in regard to theory, however training methods that align to principles of player centred, nonlinear, and representative learning design, and to ecological dynamics were expressed (Chow et al., 2016; Pinder et al., 2011). One coach detailed the importance of allowing players to learn independently:

“They don’t have to be taught like robots, if you give them a challenging task and a couple of things to focus on, they can learn themselves by playing. They’ll pick things up if you give them one thing and don’t just spoon-feed them” (Coach 3).

Adopting a player-centred approach to learning led coaches to accept that learning can be an inherently nonlinear and messy process as players explore solutions to challenges during a session (Chow, 2013):

“It’s like learning to ride a bike, you might fall off but then eventually you get it... You’ve got to go through that learning process where they don’t do it, and it doesn’t quite come off” (Coach 6).

Adjusting activities to account for differences in learning did not involve over simplifying or completely changing the task, but subtly adjusting environmental or task constraints (Davids et al., 2013). This meant that once they were using a games-based approach coaches could adapt the nature of the task without over compromising its structure, or likeness to a match. Whilst this did not mean that isolated technical practices were absent from sessions (see previous sub-theme), several coaches were able to identify the potential benefits of games-based activity:

“For me, I like games because they are relevant to a match. That means I can get across the coaching points I want to make for a game on the weekend, and the kids can picture how everything relates” (Coach 2).

This aligns with an ecological dynamics perspective of skill acquisition, and highlights that coaches have some awareness that developing a functional performer-environment relationship is a nonlinear process, influenced by interacting constraints (Davids et al., 2017; Ford & Williams, 2013). Furthermore, coaches advocated the use of games due to their relevance in match situations. By embracing match-relevant games during sessions, coaches provide players with opportunities to acquire and transfer both technical and decision-making skills into matches more effectively (Araújo et al., 2009; Chow et al., 2019; Pinder et al., 2011). Although more explicit conceptual understanding could be beneficial in helping coaches to consistently implement these approaches (Butler, 2014) these findings are somewhat encouraging.

### 3.2. *The Coaching Environment*

Within this dimension, coaches’ experiences of factors that shape their approach to player learning from within their own coaching environment are presented. Three higher order themes of club philosophies, player characteristics, and setting and learning requirements were identified.

#### 3.2.1. *Club Philosophies*

Coaches expressed how the philosophy of the club they worked at contributed to the focus and design of their sessions. Whereas some coaches worked independently, others worked at clubs that encouraged the coaches to design sessions in specific ways, or

focus on the development of certain technical skills, as one coach alluded to:

“At the club where we coach, our main focus is dribbling from the youngest age groups up. That will be ball at their feet, can they beat as many players as possible, can they do skills using different parts of the feet” (Coach 1).

Where clubs had implemented a specific philosophy, the coaches suggested that they adopted it as their own. This was particularly evident when working in more elite environments:

“At the Cat(egory) 1 and Cat(egory) 2 academies, of course they expect you to plan and develop sessions independently, but you’re very much working towards their guidelines in terms of player development” (Coach 8).

By implementing a framework for coaches to adhere to, club philosophies play an important role in determining how learning environments are created for young players. This illustrates the importance of socio-cultural constraints on the development of athlete learning (Rothwell, Davids, & Stone, 2018), and is consistent with Cushion and Partington’s (2016) notion that coaching approaches are not underpinned solely by the agency of the coach but influenced by the social structure in which they operate. Although the coaches interviewed had not experienced a situation where they strongly opposed a coaching philosophy implemented by their club, it is important to consider that club philosophies can act as a reinforcer of traditional norms that coaches can find difficult to deviate from (Blackett, Evans, & Piggott, 2019; Cushion et al., 2012; Wadsworth, Charnock, Russell, & Littlewood, 2020). Combined, these findings highlight the need to consider clubs as significant contributors to coaches’ approaches to player learning. As such, coach educators must consider how the philosophies of clubs align with their principles for practice (e.g., the England DNA) when looking to integrate contemporary pedagogical principles.

#### 3.2.2. *Player Characteristics*

Coaches approached their sessions differently depending on the characteristics (e.g., age or skill level) of the group that they were coaching. These characteristics were important considerations when planning sessions, as one coach explained:

“So, the ability level and age particularly make a difference. You need to adapt the session depending on that and that is the first thing I consider before structuring my session” (Coach 7).

With younger age groups, the sessions became more focused around the development of technical skills over tactical understanding:

“As they grow older it needs to change from a more technical focus to tactical. So being able to switch from when they are 8 and 9 years old it’s all technical, then every year you add a bit more tactical sense in, that is the challenge” (Coach 1).

Similarly, more simplistic technically focused practises were viewed as important when working with players of lesser abilities:

“With my boys now, I could try and work on transition in defence to attack. Great, set up a phase of play or complex practice. But some of them will struggle because they don’t have the basic technical skills like passing range, first touch, movement and stuff. So, we need to work on that first” (Coach 4).

As researchers have suggested (Roca et al., 2013), adopting a less binary approach that accepts the complementary relationship between the development of technique and tactical understanding can be beneficial. Perhaps most notably, this could encourage coaches to create sessions that promote technical development whilst acknowledging the need to train these skills using activities that facilitate decision-making, development of tactical awareness, and the transfer of learning into the competition environment (Chow et al., 2019; Ford & Whelan, 2016; Harvey et al., 2010). This approach to player learning and practice design requires an awareness of task simplification over task fractionation or decomposition, in the sense that practises must preserve the complexity of the activity to maintain the coupling between information and movement, and thus transfer of skills (Seifert & Davids, 2017). Coach educators must be sensitive to this and ensure that coaches are equipped with the necessary understanding to utilise and apply contemporary methods at grass roots and foundational levels (Mallett, Trudel, & Lyle, 2009; Nelson, Cushion, & Potrac, 2006).

### 3.2.3. *Setting and Learning Requirements*

The coaches expressed how they may often work in different settings whereby their approaches to learning had to be sensitive to changing learning requirements. Whilst working with their teams, the aims of the session would often revolve around team-based principles relating to either previous performances or tactical development, as one coach explained:

“This season in training I’d set one team up in a 4-3-3 as a lot of teams play that, then coach a team by letting them play against them in that formation. We’d focus on the positions they need to take up, how we attack, and how we defend against it” (Coach 3).

However, when working with players on a one-to-one basis, learning moved towards the development of technical skills that met the specific needs of that individual:

“I do a lot of one-to-one bits with pretty talented kids, but it’s great because you can really notice, break down and then improve those technical elements of their game that might not be quite up to speed” (Coach 8).

A focus on individual improvement was also commonly reported by coaches who had worked within school systems, where despite coaching in groups, the success of their session was determined by the ability to facilitate positive learning outcomes for each learner:

“That’s (schools) where you need everyone to participate and enjoy it because the levels are so varied. It can be difficult to adapt because what you need to do is challenge the kids who are really good but help the kids who are really struggling so they both get positive outcomes” (Coach 2).

Despite coaches’ views that one to one coaching provides an important source of information regarding specific technique and weaknesses, to facilitate successful learning and improvement from these sessions, coaches must allow learners to explore solutions to challenges under representative conditions as opposed to fragmented or heavily broken-down technical drills (Chow et al., 2019; Seifert & Davids, 2017). Interestingly, working in school systems encouraged coaches to think critically about how to achieve individual improvement through maintaining suitable levels of challenge for each learner within a group session (e.g., Challenge Point Framework, see Guadagnoli & Lee, 2004). Taken in combination with the previous themes within this dimension, it is evident that coaching, and consequently approaches to player learning, are complex and influenced by a multitude of social, contextual and situational factors (Jones, Edwards, & Viotto Filho, 2014; Stodter & Cushion, 2017).

### 3.3. *Opportunities for Learning and Development*

Within this dimension, coaches’ experiences of how different learning and developmental opportunities have shaped their approach to player learning are discussed. Three higher order themes of self-development, experiences of FA education, and role of other coaches were identified.

#### 3.3.1. *Self-Development*

The participants voiced how continually looking to improve as a coach was an important part of their practice:

“A massive thing for me throughout my coaching career or professional life is ‘who do I learn from?’, ‘how do I get better?’” (Coach 6).

Whilst in some cases this could involve independently evaluating and refining practice activities, the coaches expressed how knowledge gained from educational courses was also important. For many, this centred around a form of tertiary level study such as undergraduate coaching courses. The learning experiences on these courses helped develop skills like planning and reflection, but also directly influenced coaching behaviour, as one graduate coach described:

“Okay, so one thing I learnt on the course is that every player has a different personality. I cannot shout instructions at every player because it will overwhelm a certain player. You have to adapt your behaviour accordingly to get the best out of individuals” (Coach 5).

Although researchers have indicated that coaches can struggle to specify and provide rationale for the behaviours and activities they use (Cushion, 2013; Partington, Cushion, & Harvey, 2014),

experiences in higher education helped this sample of coaches to indicate how they adapt their sessions to suit the development of their players:

“I’ve been in sports science as well like you and know that different players learn differently. I think by using games players can see it, hear it, and learn to do it better. My boys can’t picture drills in a game, so they don’t like it because it’s not how they learn” (Coach 3).

These findings support the idea that the educational background of coaches influences coaching practice (Stonebridge & Cushion, 2018). Whilst formal learning environments in the form of coach accreditation schemes are often devalued by coaches (Stoszowski & Collins, 2018) opportunities for tertiary level study provided an important means of self-development that was reflected across both coach behaviours and practice activity. From an applied perspective, this could present an opportunity for coach educators to learn from professional teaching institutions (e.g., universities) when trying to identify how best to disseminate contemporary pedagogical ideas (Armour, Griffiths, & De Lyon, 2016).

### 3.3.2. *Experiences of FA Education*

The coaches had experienced a range of FA led educational opportunities. Attaining FA coaching badges was a fundamental element in the progression of the coaches’ career, and although some of these experiences preceded the FA’s revision to the coaching courses (Allison, 2016), similar viewpoints were expressed regarding the transition from the simplistic FA Level 1 to the more technically focused FA Level 2, as one coach explained:

“Yeah, I was on the new Level 1 which I am glad about, but it was still pretty basic. Enjoyable but I wouldn’t say it influenced my approach too much. The Level 2 is then when you add the detail about coaching a technique, progressing into a skill, then taking that into a match” (Coach 4).

The development of tactical game understanding came once coaches had progressed further and looked to complete their UEFA qualifications (FA Level 3 & 4):

“That’s where I learnt so much about the game, Level 2 was all technical whereas UEFA B was all tactical” (Coach 7).

The structure by which coaches suggested they had been taught during FA coaching courses was reflected in their own approach to player learning in that the technical component of skill acquisition preceded tactical and games-based practice. This may be important when considering why English youth football coaches choose to begin sessions with technically focused practices, and ultimately are able to utilise less of the session for active decision-making activity than their European counterparts (Roca & Ford, 2020).

Whilst experiences from FA coaching courses offered a useful framework for practice, the coaches articulated that some formal learning experiences had lacked guidance for practical application

in that they explain ‘*what*’ to do but less so ‘*how*’ to do it, as one coach alluded to when discussing a recent Continuing Professional Development (CPD) event:

“I remember having a discussion after... we felt it lacked a ‘this is how you do it’. There was a guy talking to us, but he was asking us how we’d develop decision making. I would have liked more direction to actually go and practice what we were trying to learn” (Coach 1).

This resonates with coach education literature that has highlighted how formal education (e.g., CPD) can lack clarity over how to practically implement the information provided (Chesterfield, Potrac, & Jones, 2010; Stodter & Cushion, 2017). From a skill acquisition perspective, this could hinder the integration of contemporary pedagogical approaches as coaches resort back to tried and trusted methods (Armour et al., 2016). Although the FA have looked to combat this through introducing the Football Association Youth Coach Education programme to support coaches practically by working in situ (Griffiths et al., 2016), only one of the coaches (Coach 5) had any experience of this.

### 3.3.3. *Role of Other Coaches*

The influence of other coaches on approaches to player learning and coach behaviours has been well documented (Cushion, 2013; Partington et al., 2014). The coaches interviewed also highlighted how observing and learning from other coaches impacted their own coaching methods:

“Yeah I’ve learnt so much from the coaches I’ve been around... Even little things about the session looking professional then all the way through to adjusting the size of areas, adding challenges, adapting and progressing sessions, then communicating with players as well” (Coach 7).

It has been suggested that imitating other coaches can hinder the integration of progressive learning approaches through promoting a ‘path dependence’ that simply follows traditional coaching cultures (Ross, Gupta, & Sanders, 2018; Stone et al., 2020). However, this sample of coaches did not highlight an explicit awareness of doing so:

“I wouldn’t say I really hold with me any of the coaching methods I experienced from a technical or tactical point of view... The moments that I have taken on board are those that really mattered to my development. More about how coaches instilled self-belief and spoke to me as a person” (Coach 6).

In this way, the coaches looked to apply a holistic view of player development that incorporated the social and mental aspects of their players’ learning which they had valued when playing (e.g., the Athletic Skills Model, see Wormhoudt, Savelsbergh, Teunissen, & Davids, 2018). The coaches also explained how learning from their peers can take a more nuanced form of critical reflection that serves to improve their practice:

“Where we are, we’ll have coach meetings every half term that focus on how we can improve what we’re doing. That will be

not just identifying areas for each of the coaches to improve on but highlighting our strengths and how to develop them further too” (Coach 8).

Clearly, other coaches are important in shaping and developing practice amongst their peers. Rather than dismiss this as a hindrance to the integration of contemporary pedagogical ideas, this rich experiential knowledge can be of value to coach educators and practitioners. Where formal environments have been criticised for their failure to account for the context in which coaches practice, and the complexities faced by individual coaches (Mallett et al., 2009; Piggott, 2012), by providing a forum for the informal sharing of ideas, the FA and other governing bodies could encourage a free, accessible and ‘open’ environment for coach learning (Piggott, 2015).

#### 4. Limitations and Future Directions

This study has provided novel insights by integrating youth football coaches’ approaches to player learning with experiential knowledge of the sources that have influenced their approach. However, as there can often be limited correspondence between coaches’ intent and practice (O’Connor, Larkin, & Williams, 2017), future research may look to observe sessions, and follow this up with interviews regarding coaches’ experiential knowledge. Such an approach would provide a more objective understanding of the implementation of different pedagogical approaches within youth football. Furthermore, despite this study investigating a cohort of English youth coaches specifically, the insights gained present an opportunity to build on this and previous research by contrasting the experiences of English coaches with coaches from different countries (Roca & Ford, 2020). Contrasting how the experiences of coaches working in different countries, and under different cultures, have influenced their coaching approach could provide an alternative means of benchmarking the development of coaching practice in England (North, 2016). There is also scope to build on the relatively small sample of English coaches used in this study, providing greater depth of understanding from within this culture, and wider range of experiences.

#### 5. Conclusion

The aim of this study was to further current understanding of player learning within English youth football, following recent qualitative research (e.g., Brackley, Barris, Tor, & Farrow, 2020; Pocock et al., 2020), which has used experiential knowledge of coaches to explore why they coach the way they do. The results indicate that while contemporary pedagogical approaches are deemed an important part of practice (Ford & Whelan, 2016), limited understanding of specific learning principles (e.g., representative learning design; transfer of learning) means that isolated technical drills remain a prominent part of player development. Approaches to player learning were not fixed, but dynamic and adaptable depending on a range of different social and contextual experiences within the coaching environment (Cushion & Partington, 2016). While it may be challenging for coach educators to demonstrate sensitivity to these when looking to implement contemporary learning approaches, coaches’ ability

to adapt and evolve their sessions depending on the requirements of their learners suggests that they possess the necessary skillset to embrace innovative and novel approaches (Butler, 2014; Stone et al., 2020). However, this is a process that will need to be facilitated by enhancing understanding and providing digestible frameworks for practice (Renshaw et al., 2019; Woods et al., 2020). Although the FA has devoted considerable attention to this (Allison, 2016), these findings align with previous research by highlighting that formal learning environments can be received indifferently by football coaches (Stodter & Cushion, 2017). To enhance their effectiveness, it is important that the coach educators disseminate contemporary pedagogical principles in a practical and easily transferable manner.

#### Conflict of Interest

The authors declare no conflict of interests.

#### Acknowledgment

No funding was received and no potential conflict of interests was identified by the authors. This research was conceived and designed by Sean Jewell and Jamie North. Data was collected and analysed by Sean Jewell. Data interpretation and manuscript preparation was undertaken by Sean Jewell, Colm Murphy, Chris Pocock and Jamie North.

#### References

- Allison, W. (2016). The FA’s Coach Education and Development Programme. In W. Allison, A. Abraham, & A. Cale (Eds.), *Advances in coach education and development: From research to practice* (pp. 1-13). Routledge.
- Araújo, D., & Davids, K. (2011). Talent development: From possessing gifts to functional environmental interactions. *Talent Development & Excellence*, 3(1), 23–25.
- Araújo, D., Davids, K., Chow, J. Y., Passos, P., & Raab, M. (2009). The development of decision making skill in sport: An ecological dynamics perspective. In D. Araújo, & H. Ripoll (Eds.). *Perspectives on cognition and action in sport* (pp. 157–169). Nova Science Publishers Inc.
- Armour, K., Griffiths, M., & De Lyon, A. (2016). CPD Provision for the football coaching workforce. In W. Allison, A. Abraham, & A. Cale (Eds.), *Advances in coach education and development: From research to practice* (pp. 30-40). Routledge.
- Ashworth, D. (2014). A Sense of Purpose. In P. Glynn (Ed.), *The boot room Issue 11* (pp. 14-18). St George’s Park: FA Education.
- Blackett, A. D., Evans, A. B., & Piggott, D. (2019). “They have to toe the line”: A Foucauldian analysis of the socialisation of former elite athletes into academy coaching roles. *Sports Coaching Review*, 8(1), 83-102. <https://www.doi.org/10.1080/21640629.2018.1436502>
- Brackley, V., Barris, S., Tor, E., & Farrow, D. (2020). Coaches’ perspective towards skill acquisition in swimming: What practice approaches are typically applied in training? *Journal of Sports Sciences*, 38(22), 2532-2542.

- Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology, 3*(2), 77-101.
- Braun, V., Clarke, V., & Weate, P. (2016). Using thematic analysis in sport and exercise research. In B. Smith & A. Sparkes (Eds.), *Routledge handbook of qualitative research methods in sport and exercise* (pp. 191–205). Routledge
- Butler, J. (2014). TGfU - would you know it if you saw it? benchmarks from the tacit knowledge of the founders. *European Physical Education Review, 20*(4), 465-488. <https://www.doi.org/10.1177/1356336X14534356>
- Cassidy, T., Jones, R. L., & Potrac, P. (2009). *Understanding sports coaching: The social, cultural and pedagogical foundations of coaching practice* (2nd ed.). Routledge.
- Chesterfield, G., Potrac, P., & Jones, R. (2010). 'Studentship' and 'impression management' in an advanced soccer coach education award. *Sport, Education and Society, 15*(3), 299-314.
- Chow, J. Y. (2013). Nonlinear learning underpinning pedagogy: Evidence, challenges, and implications. *Quest (National Association for Kinesiology in Higher Education), 65*(4), 469-484. <https://www.doi.org/10.1080/00336297.2013.807746>
- Chow, J. Y., Davids, K., Button, C., & Renshaw, I. (2016). *Nonlinear pedagogy in skill acquisition: An introduction*. Routledge.
- Chow, J. Y., Shuttleworth, R., Davids, K., & Araújo, D. (2019). Ecological dynamics and transfer from practice to performance in sport. In N. Hodges & A. M. Williams (Eds.), *Skill acquisition in sport* (pp. 163-182). Routledge.
- Clarke, V., Hayfield, N., Moller, N., & Tischner, I. (2017). Once upon a time ... Qualitative story completion methods. In V. Braun, V. Clarke, & D. Grey (Eds.), *Collecting qualitative data: A practical guide to textual, media, and virtual techniques* (pp. 45-68). University Press.
- Cushion, C. J. (2013). Coaching and coach education. In A. M. Williams (Ed.), *Science and soccer: Developing elite performers* (pp. 199-217.). Routledge.
- Cushion, C., Ford, P. R., & Williams, A. M. (2012). Coach behaviours and practice structures in youth soccer: Implications for talent development. *Journal of Sports Sciences: Identifying and Developing Elite Soccer Players, 30*(15), 1631-1641. <https://www.doi.org/10.1080/02640414.2012.721930>
- Cushion, C., & Jones, R. L. (2006). Power, discourse, and symbolic violence in professional youth soccer: The case of Albion Football Club. *Sociology of Sport Journal, 23*(2), 142-161. <https://www.doi.org/10.1123/ssj.23.2.142>
- Cushion, C., & Partington, M. (2016). A critical analysis of the conceptualisation of 'coaching philosophy'. *Sport, Education and Society, 21*(6), 851-867. <https://www.doi.org/10.1080/13573322.2014.958817>
- Davids, K., Araújo, D., Correia, V., & Vilar, L. (2013). How small-sided and conditioned games enhance acquisition of movement and decision-making skills. *Exercise and Sport Sciences Reviews, 41*(3), 154-161. <https://www.doi.org/10.1097/JES.0b013e318292f3ec>
- Davids, K., Araújo, D., Hristovski, R., Passos, P., & Chow, J. Y. (2012). Ecological dynamics and motor learning design in sport. In N. Hodges & A. M. Williams (Eds.), *Skill acquisition in sport* (pp. 112-130). Routledge.
- Davids, K., Araújo, D., Seifert, L., & Orth, D. (2015). Expert performance in sport: An ecological dynamics perspective. In J. Baker & D. Farrow (Eds), *Routledge handbook of sport expertise* (pp. 273–303). Routledge.
- Davids, K., Button, C., & Bennett, S. (2008). *Dynamics of skill acquisition: A constraints-led approach*. Human Kinetics.
- Davids, K., Gullich, A., Shuttleworth, R., & Araújo, D. (2017). Understanding environmental and task constraints on talent development: Analysis of micro-structure of practice and macro-structure of development histories. In J. Baker, S. Cobley, J. Schorer, & N. Wattie (Eds.), *Routledge handbook of talent identification and development in sport* (pp. 192–206). Abingdon.
- Davids, K., Hristovski, R., Araújo, D., Balague-Serre, N., Button, C., & Passos, P. (2014). *Complex systems in sport*. Routledge.
- Duffy, P., Hartley, H., Bales, J., Crespo, M., Dick, F., Vardhan, D., Nordmann, L., & Curado, J. (2011). Sport coaching as a 'profession'. *International Journal of Coaching Science, 5*(2), 93-123.
- FA Education. (2015). *England DNA: Connecting the Game*. St George's Park: FA Learning.
- Ford, P. R., & Whelan J. (2016). Practice activities during coaching sessions in elite youth football and their effect on skill acquisition. In W. Allison, A. Abraham, & A. Cale (Eds.), *Advances in coach education and development: From research to practice* (pp. 112-123). Routledge.
- Ford, P. R., & Williams, A. M. (2013). The acquisition of skill and expertise: The role of practice and other activities. In A. M. Williams (Eds.), *Science and soccer: Developing elite performers* (pp. 134-150). Routledge.
- Ford, P. R., Yates, I., & Williams, A. M. (2010). An analysis of practice activities and instructional behaviours used by youth soccer coaches during practice: Exploring the link between science and application. *Journal of Sports Sciences, 28*(5), 483-495. <https://www.doi.org/10.1080/02640410903582750>
- Griffiths, M., Armour, K., & De Lyon, A. (2016). Examining the impact of the FA youth coach education programme. In W. Allison, A. Abraham, & A. Cale (Eds.), *Advances in coach education and development: From research to practice* (pp. 100-111). Routledge.
- Guadagnoli, M. A., & Lee, T. D. (2004). Challenge point: a framework for conceptualizing the effects of various practice conditions in motor learning. *Journal of Motor Behavior, 36*(2), 212-224.
- Harvey, S., Cushion, C. J., & Massa-Gonzalez, A. N. (2010). Learning a new method: Teaching games for understanding in the coaches' eyes. *Physical Education and Sport Pedagogy, 15*(4), 361-382. <https://www.doi.org/10.1080/17408980903535818>
- Hodges, N. J., & Lohse, K. R. (2022). An extended challenge-based framework for practice design in sports coaching. *Journal of Sports Sciences, 40*(7), 1-15. <https://www.doi.org/10.1080/02640414.2021.2015917>
- Jones, R. L., Edwards, C., & Viotto Filho, I. A. T. (2014). Activity theory, complexity and sports coaching: An epistemology for a discipline. *Sport, Education and Society, 21*(2), 200-216. <https://www.doi.org/10.1080/13573322.2014.895713>
- Jones, R. L., Morgan, K., & Harris, K. (2012). Developing coaching pedagogy: Seeking a better integration of theory and

- practice. *Sport, Education and Society*, 17(3), 313-329. <https://www.doi.org/10.1080/13573322.2011.608936>
- Mallett, C. J., Trudel, P., Lyle, J., & Rynne, S. B. (2009). Formal vs. informal coach education. *International Journal of Sports Science & Coaching*, 4(3), 325-364. <https://www.doi.org/10.1260/174795409789623883>
- Masters, R. S. W., Van Duijn, T., & Uiga, L. (2019). Advances in Implicit Motor Learning. In N. Hodges & A. M. Williams (Eds.), *Skill acquisition in sport* (pp. 77-95). Routledge.
- Miller, A., Harvey, S., Morley, D., Nemes, R., Janes, M., & Eather, N. (2017). Exposing athletes to playing form activity: Outcomes of a randomised control trial among community netball teams using a game-centred approach. *Journal of Sports Sciences*, 35(18), 1846-1857.
- Moy, B., Renshaw, I., Davids, K., & Brymer, E. (2016). Overcoming acculturation: Physical education recruits' experiences of an alternative pedagogical approach to games teaching. *Physical Education and Sport Pedagogy*, 21(4), 386-406. <https://www.doi.org/10.1080/17408989.2015.1017455>
- Nelson, L. J., Cushion, C. J., & Potrac, P. (2006). Formal, nonformal and informal coach learning: A holistic conceptualisation. *International Journal of Sports Science & Coaching*, 1(3), 247-259. <https://www.doi.org/10.1260/174795406778604627>
- North, J. (2016). Benchmarking sport coach education and development. In W. Allison, A. Abraham, & A. Cale (Eds.), *Advances in coach education and development: From research to practice* (pp. 17-29). Routledge.
- O'Connor, D., Larkin, P., & Williams, A. M. (2017). What learning environments help improve decision-making? *Physical Education and Sport Pedagogy*, 22(6), 647-660. <https://www.doi.org/10.1080/17408989.2017.1294678>
- Partington, M., & Cushion, C. (2013). An investigation of the practice activities and coaching behaviors of professional top-level youth soccer coaches. *Scandinavian Journal of Medicine & Science in Sports*, 23(3), 374-382. <https://www.doi.org/10.1111/j.1600-0838.2011.01383.x>
- Partington, M., Cushion, C., & Harvey, S. (2014). An investigation of the effect of athletes' age on the coaching behaviours of professional top-level youth soccer coaches. *Journal of Sports Sciences*, 32(5), 403-414. <https://www.doi.org/10.1080/02640414.2013.835063>
- Patton, M. Q. (2002). *Qualitative research and evaluation methods* (3rd ed.). Sage Publications.
- Piggott, D. (2012). Coaches' experiences of formal coach education: A critical sociological investigation. *Sport, Education and Society*, 17(4), 535-554. <https://www.doi.org/10.1080/13573322.2011.608949>
- Piggott, D. (2015). The open society and coach education: A philosophical agenda for policy reform and future sociological research. *Physical Education and Sport Pedagogy*, 20(3), 283-298. <https://www.doi.org/10.1080/17408989.2013.837435>
- Pinder, R. A., Davids, K., Renshaw, I., & Araújo, D. (2011). Representative learning design and functionality of research and practice in sport. *Journal of Sport & Exercise Psychology*, 33(1), 146-155. <https://www.doi.org/10.1123/jsep.33.1.146>
- Pocock, C., Bezodis, N. E., Wadey, R., & North, J. S. (2020). Understanding key constraints and practice design in Rugby Union place kicking: Experiential knowledge of professional kickers and experienced coaches. *International Journal of Sports Science & Coaching*, 15, 631-641.
- Renshaw, I., Davids, K., Newcombe, D., & Roberts, W. (2019). *The Constraints-Led Approach: Principles for sports coaching and practice design*. Routledge.
- Renshaw, I., Headrick, J., Maloney, M., Moy, B., & Pinder, R. (2019). Constraints-led learning in practice: Designing effective learning environments. In N. Hodges & A. M. Williams (Eds.), *Skill acquisition in sport* (pp. 163-182). Routledge.
- Roca, A., & Ford, P. R. (2020). Decision-making practice during coaching sessions in elite youth football across European countries. *Science and Medicine in Football*, 4(4), 263-268. <https://www.doi.org/10.1080/24733938.2020.1755051>
- Roca, A., Ford, P. R., McRobert, A. P., & Williams, A. M. (2013). Perceptual-cognitive skills and their interaction as a function of task constraints in soccer. *Journal of Sport & Exercise Psychology*, 35(2), 144-155. <https://www.doi.org/10.1123/jsep.35.2.144>
- Roca, A., Williams, A. M., & Ford, P. R. (2012). Developmental activities and the acquisition of superior anticipation and decision making in soccer players. *Journal of Sports Sciences*, 30(15), 1643-1652. <https://www.doi.org/10.1080/02640414.2012.701761>
- Ross, E., Gupta, L., & Sanders, L. (2018). When research leads to learning, but not action in high performance sport. *Progress in Brain Research*, 240, 201-217.
- Rothwell, M., Davids, K., & Stone, J. (2018). Harnessing socio-cultural constraints on athlete development to create a form of life. *Journal of Expertise* 1(1), 94-102.
- Rothwell, M., Stone, J., & Davids, K. (2019). Exploring forms of life in player development pathways: The case of British rugby league. *Journal of Motor Learning and Development*, 7(2), 242-260. <https://www.doi.org/10.1123/jmld.2018-0020>
- Schinke, R. J., Smith, B., & McGannon, K. R. (2013). Pathways for community research in sport and physical activity: Criteria for consideration. *Qualitative Research in Sport, Exercise and Health*, 5(3), 460-468. <https://www.doi.org/10.1080/2159676x.2013.846274>
- Seifert, L., & Davids, K. (2017). Ecological dynamics: a theoretical framework for understanding sport performance, physical education and physical activity. In *First complex systems digital campus world e-conference 2015* (pp. 29-40). Springer.
- Smith, W. (2016). Fundamental movement skills and fundamental games skills are complementary pairs and should be taught in complementary ways at all stages of skill development. *Sport, Education and Society*, 21(3), 431-442. <https://www.doi.org/10.1080/13573322.2014.927757>
- Smith, B., & McGannon, K. R. (2018). Developing rigor in qualitative research: Problems and opportunities within sport and exercise psychology. *International Review of Sport and Exercise Psychology*, 11(1), 101-121. <https://www.doi.org/10.1080/1750984X.2017.1317357>
- Sparkes, A. C., & Smith, B. (2009). Judging the quality of qualitative inquiry: Criteriology and relativism in action. *Psychology of Sport and Exercise*, 10(5), 491-497. <https://www.doi.org/10.1016/j.psychsport.2009.02.006>

- Sparkes, A. C., & Smith, B. (2014). *Qualitative research methods in sport, exercise and health: From process to product*. Routledge.
- Sports Coach UK. (2008). *The UK coaching framework: Executive summary*. Sports Coach UK
- Stodter, A., & Cushion, C. J. (2017). What works in coach learning, how, and for whom? A grounded process of soccer coaches' professional learning. *Qualitative Research in Sport, Exercise and Health, 9*(3), 321-338. <https://www.doi.org/10.1080/2159676x.2017.1283358>
- Stone, J. A., Rothwell, M., Shuttleworth, R., & Davids, K. (2020). Exploring sports coaches' experiences of using a contemporary pedagogical approach to coaching: An international perspective. *Qualitative Research in Sport, Exercise and Health, 13*(4), 639-657. <https://www.doi.org/10.1080/2159676x.2020.1765194>
- Stonebridge, I., & Cushion, C. (2018). An exploration of the relationship between educational background and the coaching behaviours and practice activities of professional youth soccer coaches. *Physical Education and Sport Pedagogy, 23*(6), 636-656. <https://www.doi.org/10.1080/17408989.2018.1485143>
- Stoszowski, J., & Collins, D. (2016). Sources, topics and use of knowledge by coaches. *Journal of Sports Sciences, 34*(9), 794-802. <https://www.doi.org/10.1080/02640414.2015.1072279>
- Tracy, S. J. (2010). Qualitative quality: Eight "Big-tent" criteria for excellent qualitative research. *Qualitative Inquiry, 16*(10), 837-851. <https://www.doi.org/10.1177/1077800410383121>
- Travassos, B., Duarte, R., Vilar, L., Davids, K., & Araújo, D. (2012). Practice task design in team sports: Representativeness enhanced by increasing opportunities for action. *Journal of Sports Sciences, 30*(13), 1447-1454. <https://www.doi.org/10.1080/02640414.2012.712716>
- Wadsworth, N., Charnock, L., Russell, J., & Littlewood, M. (2020). Use of video-analysis feedback within a six-month coach education program at a professional football club. *Journal of Sport Psychology in Action, 11*(2), 1-19. <https://www.doi.org/10.1080/21520704.2018.1528324>
- Weed, M. (2009). Research quality considerations for grounded theory research in sport & exercise psychology. *Psychology of Sport and Exercise, 10*(5), 502-510. <https://www.doi.org/10.1016/j.psychsport.2009.02.007>
- Williams, S., Alder, D., & Bush, A. (2015). A little less conversation; a little more (relational) action please. A fictional dialogue of integrating theory into coaching practice. *Sports Coaching Review, 4*(2), 115-138. <https://www.doi.org/10.1080/21640629.2016.1158544>
- Williams, A. M. & Hodges, N. J. (2005). Practice, instruction, & skill acquisition in soccer: Challenging tradition. *Journal of Sports Science, 23*(6), 637-650.
- Wright, D. L., & Kim, T. (2019). Contextual Interference. In N. Hodges & A. M. Williams (Eds.), *Skill acquisition in sport* (pp. 99-118). Routledge.
- Woods, C. T., McKeown, I., O'Sullivan, M., Robertson, S., & Davids, K. (2020). Theory to practice: Performance preparation models in contemporary high-level sport guided by an ecological dynamics framework. *Sports Medicine - Open, 6*, 36. <https://www.doi.org/10.1186/s40798-020-00268-5>
- Woods, C. T., McKeown, I., Shuttleworth, R. J., Davids, K., & Robertson, S. (2019). Training programme designs in professional team sport: An ecological dynamics exemplar. *Human Movement Science, 66*, 318-326. <https://www.doi.org/10.1016/j.humov.2019.05.015>
- Wormhoudt, R. (2018). *The athletic skills model: Optimizing talent development through movement education*. Routledge.

## Reliability, variability, and minimal detectable change of bilateral and unilateral lower extremity isometric force tests

Adam M. Mattiussi<sup>1, 2, \*</sup>, Joseph W. Shaw<sup>1, 2</sup>, Daniel D. Cohen<sup>3, 4</sup>, Phil Price<sup>1</sup>, Derrick D. Brown<sup>5</sup>, Charles R. Pedlar<sup>1, 6</sup>, Jamie Tallent<sup>7, 8</sup>

<sup>1</sup>Faculty of Sport, Allied Health and Performance Science, St Mary's University, Twickenham, UK

<sup>2</sup>Ballet Healthcare, The Royal Ballet, Royal Opera House, London, UK

<sup>3</sup>Faculty of Life Sciences, University of Santander, Bucaramanga, Colombia

<sup>4</sup>Mindeporte (Colombian Ministry of Sport), High Performance Centre, Bogotá, Colombia

<sup>5</sup>Institute of Sport Science, Dance Science, University of Bern, Bern, Switzerland

<sup>6</sup>Institute of Sport, Exercise and Health, Division of Surgery and Interventional Science, University College London, UK

<sup>7</sup>School of Sport, Rehabilitation and Exercise Sciences, University of Essex, Colchester, UK

<sup>8</sup>Department of Physiotherapy, School of Primary and Allied Health Care, Faculty of Medicine, Nursing and Health Science, Monash University, Melbourne, Australia

### ARTICLE INFO

Received: 07.01.2022

Accepted: 20.04.2022

Online: 08.10.2022

Keywords:

Plantarflexion

Squat

Knee

Ankle

### ABSTRACT

*This study aimed to investigate the within- and between-session reliability, variability, and minimal detectable change (MDC) of vertical ground reaction force (vGRF) during bilateral and unilateral lower extremity maximal isometric force tests. Eighteen participants (men: n = 9, age: 27.9 ± 6.3 y, height: 1.82 ± 0.06 m, mass: 82.4 ± 10.4 kg, strength training experience: 10.4 ± 7.7 y; women: n = 9, age: 29.3 ± 8.6 y, height: 1.68 ± 0.01 m, mass: 58.0 ± 5.8 kg, strength training experience: 5.5 ± 3.6 y) attended two data collection sessions separated by 48 h. The absolute, net, and relative vGRF were calculated across bilateral and unilateral variations of the squat, standing plantarflexion, and seated plantarflexion positions. All measures of vGRF demonstrated excellent reliability and low variability within (intraclass correlation coefficients (ICC): 0.92–0.99; coefficient of variation (CV): 2.9–6.5%) and between sessions (ICC: 0.95–1.00; CV: 2.0–6.0%), across all positions. The MDC ranged between 135–276 N (5.1–14.5%), with the seated plantarflexion positions demonstrating the highest values as a percentage of the group mean (13.3–14.5%). Maximal isometric force testing during bilateral and unilateral variations of the squat, standing plantarflexion, and seated plantarflexion positions provides reliable measurement of vGRF in men and women.*

### 1. Introduction

Maximal isometric force testing is a common method used to measure lower extremity strength. Research investigating the reliability of maximal isometric force tests has largely been conducted on the isometric mid-thigh pull using a force platform and general isometric rig (Brady et al., 2020). The isometric squat and seated and standing ankle plantarflexion have been reported

in the literature, however, these investigations have used highly specialized equipment such as hack squat machines (Blazevich & Gill, 2006; Palmer et al., 2018), wall-mounted force platforms (Beckman et al., 2014), or bespoke seated force transducers (Pääsuke et al., 2000). Specialized equipment for these tests may offer limited utility in applied environments due to cost and space restrictions. Conversely, the ability to test across various positions using a force platform and general isometric rig offers science and

\*Corresponding Author: Adam Mattiussi, Faculty of Sport, Allied Health and Performance Science, St Mary's University, UK, [mattiussi.adam@gmail.com](mailto:mattiussi.adam@gmail.com)

medicine practitioners a practical approach to isometric force testing.

Whilst bilateral variations of maximal isometric force tests have been the most common positions investigated when establishing the reliability of lower extremity strength characteristics (Brady et al., 2020), there is increasing interest in unilateral variations (Bishop et al., 2019, 2021; Goodwin & Bull, 2021). Unilateral variations of maximal isometric force tests offer insights into the strength characteristics of the limb and inter-limb asymmetries thereof (Bishop et al., 2019). Inter-limb asymmetries are particularly valuable when developing criteria-led return-to-sport protocols following unilateral injury (Rohman et al., 2015), or when directing the emphasis of training in non-injured individuals (Bishop et al., 2021). A combination of bilateral and unilateral strength characteristics and asymmetries can also be used to inform programming decisions relating to exercise selection (Cohen et al., 2020; Stern et al., 2020). Limited research, however, has investigated the effect of both bilateral and unilateral stance on the reliability of strength characteristics during various isometric force tests (Blazevich & Gill, 2006).

The within-session reliability and variability of isometric force tests are well documented, with peak vertical ground reaction force (vGRF) demonstrating the greatest intraclass correlation coefficients (ICC) and smallest coefficients of variation (CV) compared with other variables (e.g., rate of force development) (Brady et al., 2020). The between-session reliability and variability of peak vGRF during isometric force testing, however, are less well documented (Brady et al., 2020). In addition to characterizing reliability, between-session ICCs can be used to calculate the minimal detectable change (MDC). The MDC has been used to establish thresholds for outcome variables, such as vGRF, enabling practitioners to differentiate signal from noise and identify a meaningful change (Howarth et al., 2021). No studies, however, have determined the MDC during the unilateral squat or bilateral or unilateral ankle plantarflexion variations of maximal isometric force tests (Brady et al., 2020). Data pertaining to the reliability, variability, and MDC in these positions would provide a basis for applied practitioners to use such methods to monitor neuromuscular changes specific to these positions and muscle groups.

This study aimed to investigate the within- and between-session reliability, variability, and MDC of vGRF measures during maximal isometric force tests across bilateral and unilateral variations of the squat, standing plantarflexion, and seated plantarflexion positions.

## 2. Methods

### 2.1. Study Design

A within-subject test-retest design was employed to investigate the reliability, variability, and MDC of vGRF during the isometric squat, standing plantarflexion, and seated plantarflexion tests. Two or more replicants were required to calculate ICCs ( $\alpha = 0.05$ ,  $\beta = 0.80$ ) based on a minimal acceptable reliability ( $\rho_0$ ) of  $\geq 0.7$  (Koo & Li, 2016) and expected reliability ( $\rho_1$ ) of  $\geq 0.9$  (Brady et al., 2020). The expected reliability of  $\geq 0.9$  was based on previous research demonstrating excellent reliability for measures of vGRF (Brady et al., 2020). *A priori* power analyses indicated that

minimum samples of eighteen participants were required to calculate the ICC ( $\alpha = 0.05$ ,  $\beta = 0.80$ ), based on two trials recorded per participant (Walter et al., 1998), a  $\rho_0$  of  $\geq 0.7$  (Walter et al., 1998), and a  $\rho_1$  of  $\geq 0.9$  (Brady et al., 2020). Internal training load was calculated for the 48h preceding testing to account for differences in training load prior to testing sessions. Internal training load was calculated using the session rating of perceived exertion method for each participant, where rating of perceived exertion using the Borg CR-10 was multiplied by session duration in minutes (Shaw et al., 2020). The time of day was standardized for each participant to account for variations in circadian rhythm (Teo et al., 2011).

### 2.2. Participants

Nineteen participants volunteered for this research, of which eight were professional ballet dancers (men:  $n = 4$ ; women:  $n = 4$ ) and eleven physically active men ( $n = 6$ ) and women ( $n = 5$ ). One participant withdrew following the first testing session resulting in eighteen participants (men:  $n = 9$ , age:  $27.9 \pm 6.3$  y, height:  $1.82 \pm 0.06$  m, mass:  $82.4 \pm 10.4$  kg, strength training experience:  $10.4 \pm 7.7$  y; women:  $n = 9$ , age:  $29.3 \pm 8.6$  y, height:  $1.68 \pm 0.01$  m, mass:  $58.0 \pm 5.8$  kg, strength training experience:  $5.5 \pm 3.6$  y). Participants were required to have not sustained an injury in the six weeks prior to data collection. Written informed consent was gained from all participants and ethical approval was provided by the local Ethics Committee in accordance with the Declaration of Helsinki.

### 2.3. Procedure

All participants attended two identical data collection sessions, separated by 48 h. The first session was used to establish within-session reliability and variability. The first and second sessions were used to establish between-session reliability, variability, and the MDC. During each session, participants performed three five-second maximal isometric contractions in the bilateral squat, unilateral squat, bilateral standing plantarflexion, unilateral standing plantarflexion, bilateral seated plantarflexion, and unilateral seated plantarflexion positions (Figure 1). All unilateral tests were completed on the right limb only to limit the number of maximal isometric contractions within the testing session. Each five-second maximal isometric contraction within a position was separated by a 20 s recovery period. A further two-minute recovery period was provided once three maximal isometric contractions were completed within a position. A standardized and progressive warm-up was completed prior to testing, including bodyweight exercises and submaximal isometric contractions across the testing positions. The vGRF data were collected using a force platform (MUSCLELAB, Ergotest Innovation AS, Stathelle, Norway) sampling at 1000 Hz. An isometric rig, with 2.5 cm adjustable vertical spacing, and a barbell (Sportesse, Somerset, United Kingdom) were used for all tests, with a 3.3 cm thick foam pad (Power Guidance, London, England) around the barbell for comfort. Bodyweight was calculated from a five-second static trial where participants were standing motionless on the force platform. Participants were required to wear their own shoes (and the same shoes) for all



Figure 1: (A) Bilateral squat (B) Unilateral squat (C) Bilateral standing plantarflexion (D) Unilateral standing plantarflexion (E) Bilateral seated plantarflexion (F) Unilateral seated plantarflexion.

testing sessions. Participants were instructed to “push maximally into the barbell” before each trial. Each trial was initiated by the researcher instructing the participant to adopt the relevant position and then counting down “3, 2, 1, push”. The force platform was zeroed prior to each set.

### 2.3.1. Isometric Squat

The barbell was placed in a high-bar back squat position on the upper trapezius. Using a goniometer, knee and hip angles were measured to 140°, where full knee and hip extension were considered 180° (Brady et al., 2020). Knee angle was calculated by positioning the fulcrum of the goniometer over the lateral epicondyle of the femur, with the stabilization arm in line with the lateral malleolus and the movement arm in line with the greater trochanter. Hip angle was calculated by positioning the fulcrum of the goniometer over the greater trochanter with the stabilization arm in line with the femur and the movement arm in line with the glenohumeral joint. During bilateral tests, the feet were positioned at hip width. For unilateral tests, the contralateral limb was held in 90° of hip flexion to maintain a neutral hip position.

### 2.3.2. Isometric Standing Plantarflexion

The barbell was placed in a high-bar back squat position. Participants were instructed to adopt a “soft knee” position (170–180°) to avoid hyperextension. Participants were also instructed to adopt a “neutral” hip position (170–180°), measured by placing the fulcrum of the goniometer over the greater trochanter with the stabilization arm in line with the femur and the movement arm in line with the glenohumeral joint. The ankle was measured to 130° of plantarflexion where neutral was considered 90°. A plantarflexed position was selected over plantar grade or relative dorsiflexion to reduce the requirement of additional equipment (i.e., a heel raise block) and account for different heel drop heights across participant shoes. Ankle angle was calculated by positioning the fulcrum of the goniometer over the lateral malleolus with the stabilization arm in line with the head of the fibular and the movement arm in line with the first metatarsophalangeal joint. The ball of the foot was placed directly

underneath the barbell. During bilateral tests, the feet were positioned at hip width. During unilateral tests, the contralateral limb position was the same as outlined in the squat protocol.

### 2.3.3. Isometric Seated Plantarflexion

The barbell was placed proximal to the patella on the quadriceps while participants were seated in 90° of knee and hip flexion. Knee and hip measurement techniques were consistent with those outlined in the squat and standing plantarflexion protocols. Ankle position was measured using the same methods outlined in the standing plantarflexion protocol. Participants were instructed to place their arms across their shoulders to avoid assistance from the upper limb. During bilateral tests, the feet were positioned at hip width. During unilateral tests, the contralateral limb was resting off the force platform to avoid assistance.

### 2.4. Statistical Analysis

Mean vGRF was extracted during static bodyweight trials and peak vGRF, hereon referred to as absolute vGRF, was extracted during maximal isometric trials directly from the force platform software. No filtering was applied to vGRF data. Body mass was calculated by dividing mean vGRF during the static bodyweight trial by the acceleration of gravity. Net and relative vGRF was calculated to account for the influence of body mass. Net vGRF was calculated by subtracting bodyweight from absolute vGRF. Relative vGRF was calculated by dividing the absolute vGRF by body mass. The mean ± standard deviation (SD) of the absolute, net, and relative vGRF was calculated from the three trials in each position.

The within-session reliability of absolute, net, and relative vGRF was established by calculating the ICCs, with 95% confidence intervals (CI), across the three trials in each position using the *irr* R package (Gamer et al., 2019). The between-session reliability of absolute, net, and relative vGRF (mean of the three trials) was established by calculating the ICCs, with 95% CI, across the two testing sessions in each position. Two-way mixed-effects models (type = agreement) were used to calculate ICCs for within- and between-session reliability (Koo & Li, 2016). The

Table 1: Within-session intraclass correlation coefficient and coefficient of variation.

Position	<i>n</i>	Absolute vGRF (N)		Net vGRF (N)		Relative vGRF (N·kg <sup>-1</sup> )	
		ICC (95% CI)	CV	ICC (95% CI)	CV	ICC (95% CI)	CV
DL Squat	18	0.99 (0.98–1.00)	2.9	0.99 (0.97–1.00)	4.1	0.97 (0.94–0.99)	2.9
SL Squat	18	0.98 (0.96–0.99)	3.5	0.98 (0.95–0.99)	5.2	0.96 (0.92–0.98)	3.5
DL Standing PF	18	0.96 (0.91–0.98)	4.4	0.94 (0.88–0.98)	6.5	0.92 (0.84–0.97)	4.4
SL Standing PF	18	0.97 (0.94–0.99)	3.2	0.96 (0.91–0.98)	5.2	0.93 (0.86–0.97)	3.2
DL Seated PF	18	0.94 (0.88–0.98)	6.1	-	-	0.93 (0.85–0.97)	6.1
SL Seated PF	18	0.95 (0.89–0.98)	5.4	-	-	0.93 (0.85–0.97)	5.4

Note: DL, Double-Leg; SL, Single-Leg; PF, Plantarflexion; ICC, Intraclass Correlation Coefficient; CV, Coefficient of Variation; vGRF, Vertical Ground Reaction Force; CI, Confidence Interval.

ICC was interpreted in line with Koo and Li (2016) where < 0.50 = poor; 0.50–0.75 = moderate; 0.75–0.90 = good; > 0.90 = excellent. The within- and between-session intra-subject variability of the absolute, net, and relative vGRF was established by computing the CV using the *EnvStats* R package (Millard, 2013). Standard error of measurement (SEM) was calculated using the following equation:

$$SEM = SD_{baseline} \sqrt{1 - ICC_{between}}$$

Where  $SD_{baseline}$  was considered the between-subject SD of the absolute, net, and relative vGRF during the first testing session, and  $ICC_{between}$  was considered the between-session ICC (Haley & Fragala-Pinkham, 2006). The MDC was calculated using the following equation:

$$MDC = 1.96 \times \sqrt{2} \times SEM$$

Following checks for outliers, normality, and equal variance, a paired samples Wilcoxon signed-rank test was used to investigate differences in the mean internal training load between sessions using the *stats* R package (R Core Team, 2020). All data processing and statistical analysis were conducted using R (version 4.0.3, R Foundation for Statistical Computing, Vienna, Austria).

### 3. Results

Differences in internal training load in the 48 h prior to the first (mean ± SD: 825 ± 886, range: 0–2460 Arbitrary Units [AU]) and second (mean ± SD: 1253 ± 1135, range: 200–3705 AU) data collection sessions ( $Z = -2.5, p = .014$ ) was observed. The within- and between-session ICC, CV, SEM, and MDC of the absolute, net, and relative vGRF are reported in Tables 1 and 2. Mean ± SD and 95% confidence intervals for the absolute, net, and relative vGRF can be found in Table 3. Box plots and individual test-retest absolute, net, and relative vGRF data are shown in Figure 2. Box plots and individual differences in absolute, net, and relative vGRF between the bilateral and unilateral variations of each testing position can be seen in Figure 3.

### 4. Discussion

We examined the reliability, variability, and MDC of maximal isometric force tests across bilateral and unilateral variations of the squat, standing plantarflexion, and seated plantarflexion positions. We found excellent within- and between-session reliability (ICC ≥ 0.92) and low variability (CV ≤ 6.5%) for absolute, net, and relative vGRF across all testing positions. This is the first study to investigate the reliability, variability, and MDC of the absolute, net, and relative vGRF during the unilateral squat and the bilateral and unilateral ankle plantarflexion positions during maximal isometric force tests.

The within-session reliability and variability of vGRF measures observed during the bilateral and unilateral squat in the present study are in line with previous research investigating these positions (Bishop et al., 2019, 2021; Brady et al., 2020). We observed excellent between-session reliability (ICC ≥ 0.99) and low between-session CVs (≤ 2.8%) during the isometric bilateral squat. Three prior studies have investigated the between-session reliability of absolute vGRF during the bilateral squat and reported ICC values greater than 0.85; two studies investigated men (Blazevich & Gill, 2006; Drake et al., 2018), and one investigated women (Palmer et al., 2018). Only one study, however, used comparable equipment to the present investigation (Drake et al., 2018), with the remaining two studies using hack squat machines (Blazevich & Gill, 2006; Palmer et al., 2018). We demonstrate excellent between-session reliability (ICC ≥ 0.95) of vGRF measures during the unilateral squat, and bilateral and unilateral variations of standing and seated plantarflexion positions. The unilateral squat and unilateral plantarflexion positions have been investigated previously, typically demonstrating ICCs greater than 0.90 (Beckman et al., 2014; Bishop et al., 2021; Blazevich & Gill, 2006). These studies, however, have used bespoke equipment, such as a wall-mounted force platform, that may not be practical in applied environments. Our findings demonstrate that maximal isometric force tests across bilateral and unilateral variations of the squat, standing plantarflexion, and seated plantarflexion positions provide reliable measures of the absolute, net, and relative vGRF. Further, our findings support the notion that multiple test positions can be executed using a general isometric rig without the need for additional equipment.

Table 2: Between-session intraclass correlation coefficient, coefficient of variation, standard error of measurement, and minimal detectable change.

Position	n	Absolute vGRF (N)				Net vGRF (N)				Relative vGRF (N·kg <sup>-1</sup> )			
		ICC (95% CI)	CV	SEM (95% CI)	MDC (%)	ICC (95% CI)	CV	SEM (95% CI)	MDC (%)	ICC (95% CI)	CV	SEM (95% CI)	MDC (%)
DL Squat	18	1.00 (0.99–1.00)	2.0	49 (0–144)	135 (5.1)	1.00 (0.99–1.00)	2.8	51 (0–150)	140 (7)	0.99 (0.97–1.00)	2.4	0.8 (0.0–2.3)	2.2 (5.8)
SL Squat	18	0.99 (0.98–1.00)	3.3	58 (0–170)	159 (7.1)	0.99 (0.98–1.00)	5.1	59 (0–173)	162 (10)	0.97 (0.93–0.99)	3.4	1.0 (0.0–3.1)	2.9 (9.2)
DL Standing PF	18	0.99 (0.96–0.99)	3.3	80 (0–236)	221 (9.3)	0.98 (0.95–0.99)	4.8	82 (0–241)	226 (13)	0.96 (0.90–0.98)	3.4	1.2 (0.0–3.5)	3.3 (9.8)
SL Standing PF	18	0.98 (0.96–0.99)	3.0	55 (0–163)	152 (8.2)	0.97 (0.93–0.99)	4.9	56 (0–166)	156 (13)	0.96 (0.89–0.98)	3.0	0.8 (0.0–2.3)	2.1 (8.0)
DL Seated PF	18	0.97 (0.92–0.99)	4.8	100 (0–295)	276 (14.5)	-	-	-	-	0.97 (0.92–0.99)	4.8	1.2 (0.0–3.6)	3.4 (12.3)
SL Seated PF	18	0.97 (0.92–0.99)	5.9	51 (0–151)	141 (13.3)	-	-	-	-	0.95 (0.86–0.98)	6.0	0.8 (0.0–2.3)	2.2 (14.3)

Note: DL, Double-Leg; SL, Single-Leg; PF, Plantarflexion; ICC, Intraclass Correlation Coefficient; CV, Coefficient of Variation; SEM, Standard Error of Measurement; MDC, Minimal Detectable Change; vGRF, Vertical Ground Reaction Force; CI, Confidence Interval.

Table 3: Mean ± SD and 95% confidence intervals for peak and relative vertical ground reaction force.

Position	Sex	n	Absolute vGRF (N)		Net vGRF (N)		Relative vGRF (N·kg <sup>-1</sup> )	
			Mean ± SD	95% CI	Mean ± SD	95% CI	Mean ± SD	95% CI
DL Squat	Female	9	1859 ± 65	1816–1902	1290 ± 65	1248–1333	32.0 ± 1.2	31.3–32.8
	Male	9	3485 ± 83	3430–3539	2677 ± 83	2622–2731	42.7 ± 1.0	42.1–43.4
SL Squat	Female	9	1588 ± 55	1552–1623	1019 ± 55	983–1055	27.4 ± 1.0	26.8–28.1
	Male	9	2909 ± 100	2844–2975	2101 ± 100	2036–2166	35.8 ± 1.2	35.1–36.6
DL Standing PF	Female	9	1813 ± 54	1778–1849	1245 ± 54	1209–1280	31.2 ± 0.9	30.6–31.9
	Male	9	2941 ± 165	2833–3048	2132 ± 165	2025–2240	36.3 ± 2.0	35.0–37.6
SL Standing PF	Female	9	1474 ± 51	1441–1508	905 ± 51	872–939	25.5 ± 0.9	24.9–26.1
	Male	9	2221 ± 68	2177–2265	1413 ± 68	1369–1457	27.3 ± 0.8	26.8–27.9
DL Seated PF	Female	9	1477 ± 65	1434–1520	-	-	25.7 ± 1.1	25.0–26.5
	Male	9	2334 ± 178	2218–2451	-	-	29.0 ± 2.2	27.5–30.4
SL Seated PF	Female	9	825 ± 44	797–854	-	-	14.3 ± 0.8	13.8–14.8
	Male	9	1294 ± 62	1254–1335	-	-	16.0 ± 0.7	15.5–16.5

Note: DL, Double-Leg; SL, Single-Leg; PF, Plantarflexion; vGRF, Vertical Ground Reaction Force; CI, Confidence Interval.

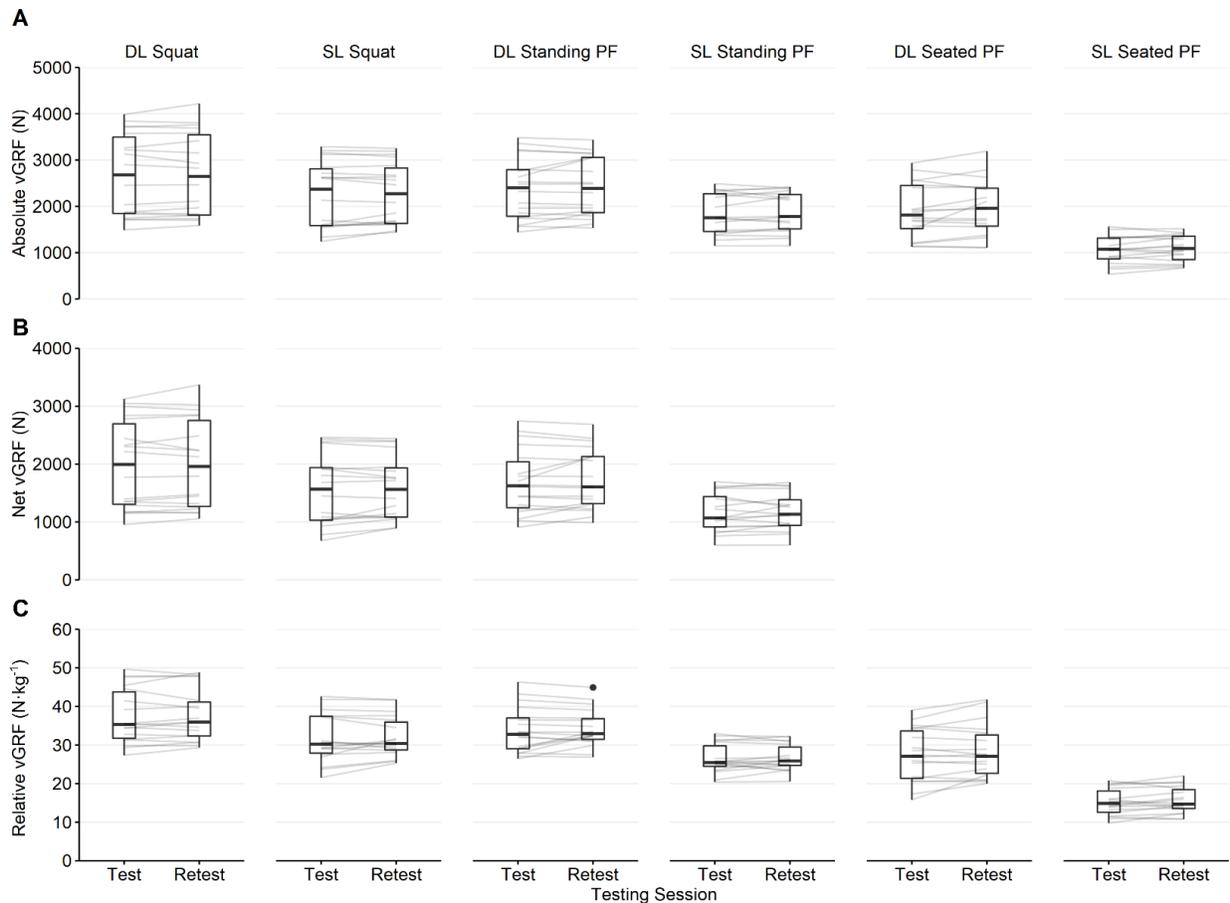


Figure 2: Box plots and individual test-retest absolute (A), net (B), and relative (C) vertical ground reaction force data. DL, Double-Leg; SL, Single-Leg; PF, Plantarflexion; vGRF, Vertical Ground Reaction Force.

The MDC for absolute vGRF ranged from 135 to 221 N (5.1–9.3% of the group mean) during bilateral and unilateral variations of the squat and standing plantarflexion positions. Previous research investigating the bilateral squat reported the MDC as 273 N (10.9%) and 230 N (~18.3%) in men and women, respectively (Drake et al., 2018; Palmer et al., 2018). Differences in study design may explain the ~100 N variation observed in the MDC between the present study and previous research. One study investigated larger knee angles using similar equipment (Drake et al., 2018), and one investigated comparable knee angles with different equipment (Palmer et al., 2018). Based on the utility of a general isometric rig in applied practice, we encourage future research to use similar equipment to the present study to facilitate comparisons. The MDC for absolute vGRF was 276 N (14.5%) and 141 N (13.3%) during bilateral and unilateral variations of seated plantarflexion, respectively. The higher MDC values (relative to the mean) may be attributed to the bar placement on the distal thigh, as it results in localized pressure and several participants reported discomfort during the test. Future research might investigate other setups, such as the use of a bespoke bar and pad that more evenly distributes pressure across the thigh.

In the present study, absolute vGRF was typically greater in the non-dancers, however, relative vGRF was typically greater in the professional dancers. Greater relative strength in the

professional ballet dancers likely reflects the training requirements associated with being a professional athlete. Across all men, absolute vGRF observed during the bilateral squat aligns with those reported in male Division 1 football and track and field athletes (Nuzzo et al., 2008) and is ~500–1000 N greater than that of collegiate rugby union players, distance runners, and amateur boxers (Brady et al., 2020). For all women, absolute vGRF observed during the bilateral squat was comparable to those reported across various sports (Brady et al., 2018). Only two studies have investigated absolute vGRF during the unilateral squat, reporting values ~1000–1500 N lower than that observed in the present study (Beckman et al., 2014; Bishop et al., 2019). Two studies have investigated plantarflexion with an extended knee; one reported similar values in recreational dancers (Rice et al., 2017) and one reported values two-thirds of that observed in the present study in recreational athletes (Beckman et al., 2014). Two studies have investigated absolute vGRF during unilateral seated plantarflexion (Kanehisa et al., 1995; Pääsuke et al., 2000) and reported values comparable to the present study. The aforementioned studies, however, tested seated plantarflexion in relative dorsiflexion (as opposed to a plantarflexed position), which is associated with optimal force production of the plantar flexors (Sale et al., 1982). It should be

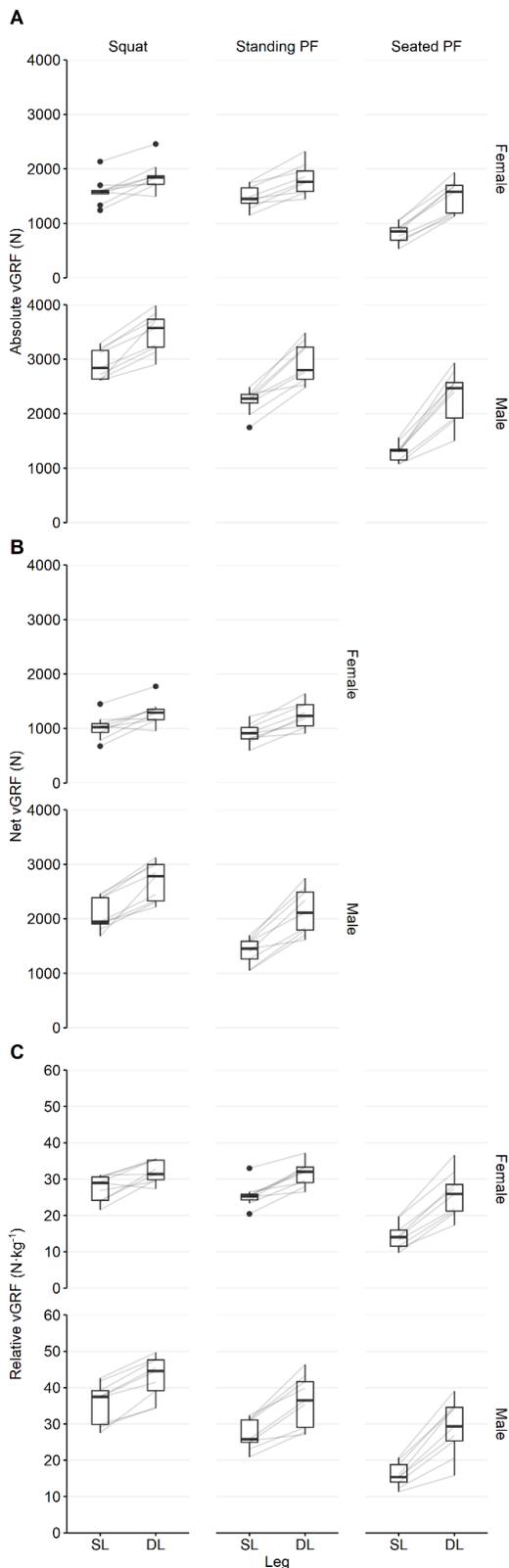


Figure 3: Box plots and individual differences in absolute (A), net (B), and relative (C) vGRF between unilateral and bilateral test positions across the squat, standing plantarflexion, and seated plantarflexion. DL, Double-Leg; SL, Single-Leg; PF, Plantarflexion; vGRF, Vertical Ground Reaction Force.

noted that although this may be associated with optimal force production, placing a participant in dorsiflexion will require additional equipment, such as a calf raise block, to ensure the heel is not in contact with the ground.

We did not outline any formal hypotheses regarding the effect of bilateral or unilateral stance on vGRF, however, we have observed several interesting findings that may direct future research. We observed relatively small differences in vGRF between bilateral and unilateral variations of the isometric squat (men: 19.9%; women: 18.2%) and standing plantarflexion position (men: 32.6%; women: 23.4%) but not seated plantarflexion position (men: 79.3%; women: 80.3%). We speculate that the limited increase in vGRF during the bilateral standing positions—compared to their unilateral counterparts—may be due to the participants’ ability to transmit force through the trunk. Larger differences in vGRF were observed between bilateral and unilateral variations of the seated plantarflexion position where the trunk is not loaded. To that end, we speculate that greater muscle mass in the trunk and upper body may moderate the transmission of force to the lower extremity and result in greater vGRF during the bilateral test (Joseph et al., 2020; Prieske et al., 2016). Further research investigating differences in absolute vGRF between bilateral and unilateral variations of standing isometric force tests is warranted.

There are several limitations to this study, for example, there may have been fatigue or potentiation effects as the order in which isometric force tests were completed was not randomized. Tests were ordered to start with the highest vGRF and finish with the lowest vGRF (e.g., bilateral squat first and unilateral seated plantarflexion last). The internal training load 48 h prior to testing was significantly different between the two sessions. The between-session reliability and variability, however, were excellent, suggesting that these tests are robust to acute changes in internal training load. This supports previous findings suggesting that vGRF measures during the mid-thigh pull are appropriate for period monitoring, but may not be sensitive to detect acute changes in neuromuscular fatigue (Norris et al., 2019). The left limb was not tested, nor was limb dominance established, which may have revealed additional insights into the reliability associated with limb dominance (Matinlauri et al., 2019). Previous research has demonstrated differences in vGRF between dominant and non-dominant limbs during the unilateral squat, however, the effect size was small with differences in reported values of ~70 N (Bishop et al., 2021). Finally, the smallest possible vertical increment of the isometric rig was 2.5 cm, limiting the precise individual adjustment of bar height.

## 5. Practical Applications

This study demonstrates that bilateral and unilateral variations of the squat, standing plantarflexion, and seated plantarflexion positions provide reliable measures of the absolute, net, and relative vGRF. For simplicity, practitioners may wish to utilise one measure of vGRF in practice due to comparable reliability and variability across absolute, net, and relative vGRF. We observed similarities in vGRF between bilateral and unilateral variations of the isometric squat and standing plantarflexion positions. We speculate that bilateral variations of axially loaded tests may not reflect the true strength characteristics of the lower extremity and might be limited by the participants' ability to

transmit higher forces through the trunk. The unilateral squat may therefore be a preferable test when aiming to measure lower extremity strength. Conversely, where an athlete's ability to transmit high forces through the entire kinetic chain in a bilateral stance is of interest, the inclusion of the bilateral squat in a testing battery is warranted. This study provides reference absolute, net, and relative vGRF data for men and women, alongside the MDC, which can facilitate criteria-based decision-making in applied environments.

## 6. Conclusion

This is the first study to investigate the within- and between-session reliability, variability, and the MDC of vGRF measures during bilateral and unilateral variations of the isometric squat, standing plantarflexion, and seated plantarflexion positions. All test positions demonstrated excellent within- and between-session reliability alongside low variability. The maximal isometric force tests investigated in the present study are a time-effective option to measure lower extremity vGRF using only a general isometric rig and force platform. Further, when interpreting a meaningful change, absolute vGRF values between 135–221 N (5.1 to 9.3% of the group mean) in standing and 141–276 N (13.3–14.5% of the group mean) in sitting can be used as benchmarks.

## Conflict of Interest

The authors declare no conflict of interests. No funding was received for the completion of this study which forms part of the lead author's PhD research.

## Contributorship

All authors contributed to the conception and design of the work. AM and JS completed the data analysis. AM wrote the first draft and prepared all revisions. All authors reviewed and edited drafts and approved the final manuscript.

## Acknowledgment

The authors would like to thank the staff, artists, and friends of The Royal Ballet for participating in this research.

## Patient Involvement

There was no patient or public involvement in the design, conduct or reporting of this study.

## References

Beckman, E. M., Newcombe, P., Vanlandewijck, Y., Connick, M. J., & Tweedy, S. M. (2014). Novel strength test battery to permit evidence-based paralympic classification. *Medicine*, 93(4), 1–8. <https://doi.org/10.1097/MD.0000000000000031>

Bishop, C., Read, P., Lake, J., Loturco, I., Dawes, J., Madruga, M., Romero-Rodrigues, D., Chavda, S., & Turner, A. (2019). Unilateral isometric squat: Test reliability, interlimb asymmetries, and relationships with limb dominance. *Journal of Strength and Conditioning Research*, 35, S144-S151.

<https://doi.org/10.1519/jsc.0000000000003079>

Bishop, C., Read, P., Lake, J., Loturco, I., & Turner, A. (2021). A novel approach for athlete profiling: The unilateral dynamic strength index. *Journal of Strength and Conditioning Research*, 35(4), 1023–1029. <https://doi.org/10.1519/JSC.0000000000002871>

Blazevich, A. J., & Gill, N. D. (2006). Reliability of unfamiliar, multijoint, uni- and bilateral strength tests: Effects of load and laterality. *Journal of Strength and Conditioning Research*, 20(1), 226–230. <https://doi.org/10.1519/R-14613.1>

Brady, C. J., Harrison, A. J., & Comyns, T. M. (2020). A review of the reliability of biomechanical variables produced during the isometric mid-thigh pull and isometric squat and the reporting of normative data. *Sports Biomechanics*, 19(1), 1–25. <https://doi.org/10.1080/14763141.2018.1452968>

Brady, C. J., Harrison, A. J., Flanagan, E. P., Gregory Haff, G., & Comyns, T. M. (2018). A comparison of the isometric midthigh pull and isometric squat: Intraday reliability, usefulness, and the magnitude of difference between tests. *International Journal of Sports Physiology and Performance*, 13(7), 844–852. <https://doi.org/10.1123/ijsp.2017-0480>

Cohen, D., Burton, A., Wells, C., Taberner, M., Diaz, M. A., & Graham-Smith, P. (2020). Single vs double leg countermovement jump tests; not half an apple! *Aspetar Sports Medicine Journal*, 9, 34–41.

Drake, D., Kennedy, R., & Wallace, E. (2018). Familiarization, validity and smallest detectable difference of the isometric squat test in evaluating maximal strength. *Journal of Sports Sciences*, 36(18), 2087–2095. <https://doi.org/10.1080/02640414.2018.1436857>

Gamer, M., Lemon, J., Fellows, I., & Singh, P. (2019). *irr: Various coefficients of interrater reliability and agreement* (R package version 0.84.1). <https://cran.r-project.org/package=irr>

Goodwin, J. E., & Bull, A. M. J. (2021). Novel assessment of isometric hip extensor function. *Journal of Strength and Conditioning Research*. Advance online publication. <https://doi.org/10.1519/JSC.0000000000004012>

Haley, S. M., & Fragala-Pinkham, M. A. (2006). Interpreting change scores of tests and measures used in physical therapy. *Physical Therapy*, 86(5), 735–743. <https://doi.org/10.1093/ptj/86.5.735>

Howarth, D. J., Cohen, D. D., McLean, B. D., & Coutts, A. J. (2021). Establishing the noise: Interday ecological reliability of countermovement jump variables in professional rugby union players. *Journal of Strength and Conditioning Research*. Advance online publication. <https://doi.org/10.1519/JSC.0000000000004037>

Joseph, L., Reilly, J., Sweezey, K., Waugh, R., Carlson, L. A., & Lawrence, M. A. (2020). Activity of trunk and lower extremity musculature: Comparison between parallel back squats and belt squats. *Journal of Human Kinetics*, 72(1), 223–228. <https://doi.org/10.2478/hukin-2019-0126>

Kanehisa, H., Yata, H., Ikegawa, S., & Fukunaga, T. (1995). A cross-sectional study of the size and strength of the lower leg muscles during growth. *European Journal of Applied Physiology and Occupational Physiology*, 72(1), 150–156. <https://doi.org/10.1007/BF00964130>

Koo, T. K., & Li, M. Y. (2016). A guideline of selecting and reporting intraclass correlation coefficients for reliability

- research. *Journal of Chiropractic Medicine*, 15(2), 155–163. <https://doi.org/10.1016/j.jcm.2016.02.012>
- Matinlauri, A., Alcaraz, P. E., Freitas, T. T., Mendiguchia, J., Abedin-Maghanaki, A., Castillo, A., Martínez-Ruiz, E., Carlos-Vivas, J., & Cohen, D. D. (2019). A comparison of the isometric force fatigue-recovery profile in two posterior chain lower limb tests following simulated soccer competition. *PLoS One*, 14(5), e0206561. <https://doi.org/10.1371/journal.pone.0206561>
- Millard, S. (2013). *EnvStats: An R package for environmental statistics*. Springer. <https://www.springer.com>
- Norris, D., Joyce, D., Siegler, J., Clock, J., & Lovell, R. (2019). Recovery of force–time characteristics after Australian rules football matches: Examining the utility of the isometric midhigh pull. *International Journal of Sports Physiology and Performance*, 14(6), 765–770. <https://doi.org/10.1123/ijsspp.2018-0349>
- Nuzzo, J. L., McBride, J. M., Cormie, P., & McCaulley, G. O. (2008). Relationship between countermovement jump performance and multijoint isometric and dynamic tests of strength. *Journal of Strength and Conditioning Research*, 22(3), 699–707. <https://doi.org/10.1519/JSC.0b013e31816d5eda>
- Pääsuke, M., Ereline, J., Gapeyeva, H., Sirkel, S., & Sander, P. (2000). Age-related differences in twitch contractile properties of plantarflexor muscles in women. *Acta Physiologica Scandinavica*, 170(1), 51–57. <https://doi.org/10.1046/j.1365-201X.2000.00753.x>
- Palmer, T. B., Pineda, J. G., & Durham, R. M. (2018). Effects of knee position on the reliability and production of maximal and rapid strength characteristics during an isometric squat test. *Journal of Applied Biomechanics*, 34(2), 111–117. <https://doi.org/10.1123/jab.2017-0213>
- Prieske, O., Muehlbauer, T., & Granacher, U. (2016). The role of trunk muscle strength for physical fitness and athletic performance in trained individuals: A systematic review and meta-analysis. *Sports Medicine*, 46(3), 401–419. <https://doi.org/10.1007/s40279-015-0426-4>
- R Core Team. (2020). *R: A language and environment for statistical computing*. <https://www.r-project.org/>
- Rice, P. E., van Werkhoven, H., Dejournette, D. J., Gurchiek, R. D., Mackall, J. W., & McBride, J. M. (2017). A comparison of musculo-articular stiffness and maximal isometric plantar flexion and knee extension force in dancers and untrained individuals. *Journal of Dance Medicine & Science*, 21(4), 144–150. <https://doi.org/10.12678/1089-313X.21.4.144>
- Rohman, E., Steubs, J. T., & Tompkins, M. (2015). Changes in involved and uninvolved limb function during rehabilitation after anterior cruciate ligament reconstruction. *The American Journal of Sports Medicine*, 43(6), 1391–1398. <https://doi.org/10.1177/0363546515576127>
- Sale, D., Quinlan, J., Marsh, E., McComas, A. J., & Belanger, A. Y. (1982). Influence of joint position on ankle plantarflexion in humans. *Journal of Applied Physiology Respiratory Environmental and Exercise Physiology*, 52(6), 1636–1642. <https://doi.org/10.1152/jappl.1982.52.6.1636>
- Shaw, J. W., Springham, M., Brown, D. D., Mattiussi, A. M., Pedlar, C. R., & Tallent, J. (2020). The validity of the session rating of perceived exertion method for measuring internal training load in professional classical ballet dancers. *Frontiers in Physiology*, 11, 1–8. <https://doi.org/10.3389/fphys.2020.00480>
- Stern, D., Gonzalo-Skok, O., Loturco, I., Turner, A., & Bishop, C. (2020). A comparison of bilateral vs. unilateral-biased strength and power training interventions on measures of physical performance in elite youth soccer players. *Journal of Strength and Conditioning Research*, 34(8), 2105–2111. <https://doi.org/10.1519/JSC.0000000000003659>
- Teo, W., McGuigan, M. R., & Newton, M. J. (2011). The effects of circadian rhythmicity of salivary cortisol and testosterone on maximal isometric force, maximal dynamic force, and power output. *Journal of Strength and Conditioning Research*, 25(6), 1538–1545. <https://doi.org/10.1519/JSC.0b013e3181da77b0>
- Walter, S. D., Eliasziw, M., & Donner, A. (1998). Sample size and optimal designs for reliability studies. *Statistics in Medicine*, 17(1), 101–110. [https://doi.org/10.1002/\(SICI\)1097-0258\(19980115\)17:1<101::AID-SIM727>3.0.CO;2-E](https://doi.org/10.1002/(SICI)1097-0258(19980115)17:1<101::AID-SIM727>3.0.CO;2-E)

## Characteristics of elite cricket fast bowlers who do and do not sustain a lumbar bone stress injury: Multifactorial analysis over 4 years

Anthony Lucente<sup>1,2</sup>, Anna Saw<sup>3\*</sup>, Kevin Sims<sup>4</sup>, Richard Saw<sup>5</sup>, Alex Kountouris<sup>3,6</sup>, Rian Crowther<sup>3</sup>

<sup>1</sup>Physiosports Brighton, VIC, Australia

<sup>2</sup>Cricket Victoria, VIC, Australia

<sup>3</sup>Cricket Australia, VIC, Australia

<sup>4</sup>Queensland Sports Medicine Centre, QLD, Australia

<sup>5</sup>Australian Institute of Sport, ACT, Australia

<sup>6</sup>La Trobe Sport and Exercise Medicine Research Centre, La Trobe University, VIC, Australia

### ARTICLE INFO

Received: 01.11.2021

Accepted: 31.05.2022

Online: 21.10.2022

### Keywords:

Spine

Vertebra

Stress fracture

Biomechanics

Workload

Screening

### ABSTRACT

Lumbar bone stress injuries (LBSI) are the highest time-loss injuries among elite adult and adolescent male cricket fast bowlers. Previous research in these cohorts has not identified any consistent stand-alone risk-factors beyond younger age. The purpose of this study was to address gaps in existing research by retrospectively reviewing four-seasons of data from male and female fast bowlers across multiple domains. Data of elite male and female fast bowlers was retrieved from Cricket Australia's online database for the seasons 2016-17 to 2019-20. Bowlers who sustained a LBSI during a season, denoted 'injured' (n = 43: 33 male, 10 female) were compared to bowlers who did not sustain a LBSI in the previous four years, denoted 'non-injured' (n = 28: 18 male, 10 female). Musculoskeletal screening, bowling technique, and bowling frequency were compared between injured and non-injured bowlers using univariate and multivariate analyses. History of any LBSI previously (odds ratio 8.84 [1.08–37.59], p = 0.003), younger age (odds ratio 0.73 [0.61–0.86], p > 0.001), and more days bowled in the previous four weeks (1.19 [1.03–1.38], p = 0.018) explained 45% of LBSI risk in elite fast bowlers. The remaining 55% was not explained by any individual, musculoskeletal, or technique variables across all bowlers. Practitioners should take into consideration any history of LBSI and the age of the bowler when prescribing bowling frequency to reduce the risk of LBSI. An individualised and adaptive approach to fast bowler preparation may also address other factors such as musculoskeletal characteristics or bowling technique if deemed relevant to the individual at the time.

### 1. Introduction

Lumbar bone stress injuries (LBSI) are the highest time-loss injuries among elite male cricket fast bowlers (Frost & Chalmers, 2014; Goggins et al., 2020; Johnson et al., 2012; Orchard et al., 2016). While LBSI are currently reported to be less common in female cricket players (Jacobs et al., 2021), they have also resulted in considerable time-loss in elite female fast bowlers (Perera et al., 2019). In fast bowlers, bone stress develops in the posterior elements of the lumbar vertebrae when the repetitive and high-force nature of the bowling action exceeds the tissue capacity (Johnson et al., 2012). The balance between the load on the lumbar vertebrae and the tissue capacity is determined by a multitude of factors such as age and musculoskeletal

characteristics, bowling technique, and bowling frequency (Johnson et al., 2012).

Younger bowlers, particularly under 22 years, are purported to be at increased risk of LBSI due to a combination of skeletal immaturity and training age capability (Blanch et al., 2015; Cyron & Hutton, 1978; Farfan et al., 1976). Two studies which have investigated musculoskeletal risk factors of LBSI in young male fast bowlers over one season identified a lower medial longitudinal arch of the foot (Foster, 1989); and shorter lumbar extension endurance, poor lumbopelvic stability, and larger knee valgus on single-leg decline squat (Bayne et al., 2016). A recent study investigated LBSI risk factors in a much larger cohort of adolescent male fast bowlers over five seasons and did not corroborate the previously identified risk factors, but did identify

\*Corresponding Author: Anna Saw, Cricket Australia, Australia. [Anna.Saw@cricket.com.au](mailto:Anna.Saw@cricket.com.au)

younger age, taller height, and poorer Star-Excursion Balance Test performance as risk factors (Sims et al., 2021). Research has yet to evaluate musculoskeletal risk factors in adult male and female bowlers, or adolescent female bowlers.

Bowling technique characteristics such as excessive shoulder counter-rotation, thoracolumbar lateral flexion at front foot contact and ball release, and increased flexion of the hip and knee at back foot contact have all been associated with LBSI in young and adult male bowlers (Alway et al., 2020; Bayne et al., 2016; Elliott et al., 1992; Foster et al., 1989; Portus et al., 2004). Similarly, a more extended or extending hip and knee joint during the latter phases of the bowling action has been attributed with bowlers having a greater risk of LBSI; noting these bowlers also experience higher peak forces (Portus et al., 2004) and bowl faster which places them at higher risk of LBSI (Elliott et al., 1992; Foster et al., 1989). While there is some agreement across these studies, the specific contribution of bowling technique to LBSI risk remains unclear.

Acute spikes in bowling frequency have been associated with increased risk of any injury in subsequent weeks in elite male fast bowlers (Orchard et al., 2015b; Orchard et al., 2009). A high bowling frequency (>234 balls) over seven days at any time in the season has been associated with lumbar stress fractures in elite male fast bowlers (Alway et al., 2019a). Conversely, bone stress injuries in elite male fast bowlers have been associated with a high bowling frequency over a few months on a background of low career bowling loads (Orchard et al., 2015a). The number of days between bowling sessions has been shown to be a pertinent aspect of bowling frequency in young male bowlers (Dennis et al., 2005; Kountouris et al., 2019), however this has not been directly investigated in adult male and female bowlers. Further research is needed to understand whether bowling frequency is a stand-alone risk factor for LBSI, directly related to the rate of bone damage exceeding the rate of repair (Robling, 2006), or whether there is an interplay with other factors such as strength and technique.

Collectively, the literature suggests that several factors relating to musculoskeletal characteristics, bowling technique, and bowling frequency may increase the risk of LBSI in fast bowlers. However, beyond younger age, there are no consistent stand-alone risk factors. Instead, the interplay of two or more factors may be more meaningful. For instance, a certain bowling technique factor may only pose an increased risk if coupled with a certain musculoskeletal characteristic. Injury risk may also develop over multiple seasons, so a bowler with certain characteristics may not develop a LBSI in one season but may be injured in the following season. A further gap in the literature is that risk factors for LBSI in female fast bowlers have not been investigated. The purpose of this study was to address gaps in existing research by retrospectively reviewing four cricket seasons of data from elite male and female fast bowlers across multiple domains, comparing bowlers who sustained a LBSI to those who did not sustain any LBSI in the previous four years.

## 2. Methods

### 2.1. Study design

Retrospective cohort study. Ethics approval was attained from the La Trobe University Human Research Ethics Committee

(HEC20058). Data were retrieved from Cricket Australia's online database (Athlete Management System, Fair Play Pty Ltd.).

### 2.2. Participants

177 Australian fast bowlers (107 male, 70 female) participated in elite senior state and national cricket programs over four seasons (2016–17 to 2019–20, season from July to March). A bowler is defined as a 'fast' bowler if they deliver (bowl) the ball at a pace which requires the wicket-keeper to stand back from the stumps to receive the ball (as opposed to slow bowlers where the wicket-keeper stands just behind the stumps).

During the study period, 43 bowlers (33 male, 10 female) who did not have a LBSI at the start of the study period sustained a LBSI and were designated to the 'injured' group. Bowlers who sustained multiple LBSI were included once for their most recent injury. A 'non-injured' group of bowlers ( $n = 28$ : 18 male, 10 female) was included for comparison based on the following criteria: i) participated in the 2019-20 season (most recent complete season when this study was conducted), ii) had been in the state or national cricket program since July 2016, iii) had not sustained a LBSI since July 2016, and iv) had no other injury or illness which made them unavailable to train or play for more than four weeks consecutively since July 2016 (potential to confound data).

### 2.3. Procedures

#### 2.3.1. Injury

A LBSI was defined as a region of bone stress in the posterior elements (pars, pedicle, lamina) of the lumbar vertebrae which was confirmed by magnetic resonance imaging (MRI) (abnormal bone marrow oedema +/- fracture) and required the bowler to stop bowling for a period of time (time-loss injury). A minimum time off was not defined, however the minimum number of days off for injuries which met the injury definition was 23 days. Some injuries were asymptomatic, identified through routine screening at the end of the season and managed with time off bowling – the methods used to describe whether asymptomatic bone stress was considered clinically relevant and required time-off bowling have been previously described (Kountouris et al., 2019; Sims et al., 2019). A recurrent LBSI occurred at the same site as a previous LBSI after successfully returning to match availability as a bowler following the previous injury. Return to match availability was determined by the team doctor and physiotherapist, based upon clinical assessments, imaging, and clinical judgement for each individual bowler. Previous LBSI were described as healed if the fracture (if present) was reported as united and bone marrow oedema resolved on follow-up MRI.

#### 2.3.2. Musculoskeletal screening

Cricket players routinely complete a musculoskeletal screening assessment prior to the start of the cricket season (between June and October). The assessments are standardised and performed by a team physiotherapist. The most recent screening during the study period was selected for non-injured bowlers, and the most recent screening prior to injury was selected for injured bowlers.

In some cases, assessments were not completed annually, hence the most recent season with data available may have been one (injured  $n = 8$ ) or two (injured  $n = 1$ ) seasons prior.

Screening assessments included: height, lower limb length (sitting height subtracted from height), weight, ankle dorsiflexion range of motion (Dennis et al., 2008), Star Excursion Balance Test (Hertel et al., 2006), lumbar lateral flexion (Nealon & Cook, 2018), trunk rotation (Johnson & Grindstaff, 2010), Modified Thomas hip extension (Kendall et al., 1993), active knee extension (Dennis et al., 2008), passive hip internal rotation (Nussbaumer et al., 2010), bent knee fall out (Malliaras et al., 2009), Biering-Sorenson test (Biering-Sorensen, 1984), hip abduction and adduction strength (Thorborg et al., 2010), groin squeeze strength (Delahunt et al., 2011), hip flexion and extension strength (Thorborg et al., 2010), lumbopelvic control (Mills et al., 2005), Beighton Hypermobility Scale (Smits-Engelsman et al., 2011), single leg hamstring bridge (Freckleton et al., 2014), single leg decline squat (Bayne et al., 2016), and calf raises (Dennis et al., 2008). Test procedures are detailed in Supplementary Table 1. When a test involved assessing lower limbs separately, the limb side was denoted as either front foot (FF: the foot contralateral to the bowling arm) or back foot (BF: the foot ipsilateral to the bowling arm).

### 2.3.3. *Bowling technique*

Cricket players routinely complete a three-dimensional (3-D) bowling technique assessment at a time of convenience throughout the year. The assessments are performed in an indoor environment with a full length run up. The most recent screening during the study period was selected for non-injured bowlers, and the most recent screening prior to injury was selected for the injured bowlers. In some cases, assessments were not completed annually, hence the most recent season with data available may have been one (injured  $n = 6$ , non-injured  $n = 4$ ), two (injured  $n = 7$ , non-injured  $n = 4$ ), or three or more (injured  $n = 1$ , non-injured  $n = 4$ ) seasons prior.

A standard protocol was used for biomechanical assessments that included the bowler performing their warm-up and several warm-up deliveries. The assessment consisted of the bowler bowling 18 deliveries, each aimed at a specific region on the pitch: full length (yorker), good length, or bouncer. Ball speed was captured with a radar (Stalker Pro II radar, 34.7 GHz) mounted in front of the bowler approximately 20 metres from the point of delivery at a height of approximately two metres.

Deliveries were recorded by a 20 camera Vicon Motion Analysis System (Oxford Metrics, Oxford UK) operating at 250 Hz. Sixty-three, 14mm diameter, spherical reflective markers were attached to bony landmarks using adhesive and double-sided tape according to a previously described Vicon plug-in-gait upper body model and lower limb marker set and model (Schache et al., 2006).

Data processing involved selecting six deliveries to three specific regions (two at each region) in addition to the maximum ball speed achieved. Marker trajectories were filtered using a fourth-order low-pass Butterworth filter with cut-off frequency of 10Hz. Back foot flat (BFF) was defined as the lowest point of the calcaneus marker following the foot contacting the ground (Ranson et al., 2008). Front foot contact (FFC) was defined as the

first frame the forefoot contacted the ground (Ranson et al., 2008; Worthington et al., 2013), both determined from marker trajectories. A simple method of determining ball release (BR) was calculated from a high-speed camera (Bonita 720c, 125fps) placed perpendicular to the bowling crease and was defined as one frame prior to the first frame that the ball was no longer in contact with the hand (Wells et al., 2015).

The laboratory coordinate system was defined as the y-axis orientation along the length of the pitch (positive in the direction of travel), the x-axis orientation along the width of the pitch (positive to the right of the bowler in the direction of travel) and the z-axis orientation vertically (positive upwards). For each segment the y-axis was orientated forwards with positive in the direction of travel, the x-axis bisected this with positive towards the bowler's right, and the z-axis orientated along the longitudinal axis. The orientation of each segment in the laboratory co-ordinate system was such that rotation about the x-axis was flexion-extension, about the y-axis was adduction-abduction, and about the z-axis longitudinal rotation. All segment and joint angles were calculated as Cardan angles, using an xyz sequence except for thorax and pelvis segments that were calculated using zyx (Baker, 2001). Anatomical position is  $180^\circ$ ; flexion, contralateral side flexion, rotation and anterior tilt is  $<180^\circ$ .

To align this research with previous cricket biomechanics literature the following segments were defined. The shoulder segment was defined by projecting a three-dimensional line between the left and right acromia in the transverse (Ranson et al., 2008). Thorax segment was defined by previously described Vicon plug-in-gait upper body model and pelvis segment marker set and model (Schache et al., 2006). The shoulder and pelvis segments were measured relative to the laboratory co-ordinate system. Shoulder counter-rotation was calculated by subtracting the maximum shoulder angle after BFF from the shoulder angle at the point of BFF about the z-axis or transverse plane (Portus et al., 2004). Hip-shoulder separation angle was calculated by subtracting the shoulder angle from the pelvis angle at BFF about the z-axis or transverse plane (Portus et al., 2004). Lateral flexion was defined as the rotation of the thorax about the pelvis in the y-axis or frontal plane (Bayne et al., 2016). Thoraco-pelvic extension was defined as the rotation of the thorax about the pelvis in the x-axis or sagittal (Alway et al., 2020).

### 2.3.4. *Bowling frequency*

The number of balls bowled in training and matches was recorded by the bowler in a custom database with mobile application interface (Athlete Management System, Fair Play Pty Ltd.). Bowling frequency (balls and days bowled) was calculated as averages over the previous four-, 12-, and 52-week windows calculated from the end of the respective Australian cricket season (March 31) for non-injured bowlers or from the date of injury diagnosis for injured bowlers.

## 2.4. *Analysis*

Analysis was completed using SPSS (version 25, IBM, Armonk, NY, USA). Independent samples T-tests were used to compare individual characteristics of male and female bowlers. Independent samples median tests were used to compare bowling

frequency variables of male and female bowlers. Limited research on elite female fast bowlers has demonstrated differences in bowling technique compared to elite male fast bowlers (Felton et al., 2019). However, visual inspection of scatterplots revealed no notable increase in variability by combining male and female data across technique data, nor musculoskeletal and bowling frequency data. Therefore, we determined it was reasonable to conduct analyses on grouped male and female data, with further analysis by sex for any variables found to be of potential interest from the grouped analysis. Variability was increased for height, weight, lower limb length (consistent with Stuelcken et al., 2007), and ball speed so these were analysed separately for males and females.

Visual inspection of frequency histograms revealed data was not normally distributed for all variables, however, was acceptable for linear regression. For accuracy and consistency, central tendency is reported as median and interquartile range (IQR) for all variables. Proportions were calculated with a Wilson 95% confidence interval (CI).

To compare injured and non-injured groups, analyses were performed using binary logistic regression (method: enter) with injury as the dependent variable and non-injured bowlers acting as the control. Univariate analyses were conducted on all variables for all bowlers. Results of the univariate analysis informed variables included in multivariate analysis. To reduce the number of Type 1 errors from analysing a large number of variables (n=110), a Bonferroni-corrected p-value of 0.0005 was set as the absolute cut-off for inclusion in the multivariate analysis. However, it is necessary to acknowledge the elite athlete cohort and relatively small sample size which preclude such a small statistical cut-off. Hence, we also applied clinical judgement and

previous research to decide on variables which may be significant in practice for inclusion in the multivariate analyses. Linear regression with collinearity diagnostics were used to assess multicollinearity.

### 3. Results

Most LBSI occurred on the side contralateral to the bowling arm (81% [95% CI 67–90]) and at levels L4 (42% [28–57]) and L5 (33% [20–47]) (Table 1). Twenty-seven bowlers (63% [48–76]) had a history of LBSI either at the same or different location to the LBSI included in this study. Of these, 22 LBSI were recurrent injuries, occurring a median of 161 (79–640) days since returning to match availability following the previous LBSI. Fourteen of the 22 bowlers with recurrent LBSI also had a history of LBSI at a different location. Nine of the 28 non-injured bowlers had a history of LBSI, occurring a median of 1997 (1955–2279) days (approximately 5–6 years) prior to the end of the study capture. The likelihood of LBSI increased by a factor of 3.94 (1.43–10.83) ( $p = 0.008$ ) if bowlers had a history of any LBSI previously.

Individual characteristics of injured bowlers and non-injured bowlers are presented in Table 2. Comparing male and female bowlers, there was no difference in age ( $p = 0.219$ ), however male bowlers were taller, had longer lower limb lengths, and higher weight (all  $p < 0.001$ ). Comparing injured and non-injured bowlers, injured bowlers were younger ( $p = 0.007$ ), with the likelihood of injury reducing by a factor of 0.85 (0.76–0.96) with each year older. Injured bowlers did not statistically differ on any musculoskeletal characteristics (Table 3) or bowling technique (Table 4) variables.

Table 1: Injury details and injury history of injured bowlers

	Male (n=33)	Female (n=10)	All (n=43)	All percent (95% CI)
<b>Injured side relative to bowling arm</b>				
Contralateral	27	8	35	81 (67-90)
Ipsilateral	5	1	6	14 (7-27)
Bilateral	1	1	2	5 (1-15)
<b>Injured lumbar vertebrae</b>				
L2	2	0	2	5 (1-15)
L3	3	0	3	7 (2-19)
L4	16	2	18	42 (28-57)
L5	9	5	14	33 (20-47)
Multiple	3	3	6	14 (7-27)
<b>Recurrent injury (n=22)</b>				
Recurrent, previously healed	9	1	10	48 (28-68)
Recurrent, previous did not heal <sup>a</sup>	10	1	11	52 (32-72)
<b>History of other LBSI (n=20)</b>				
Other LBSI, same level	6	1	7	35 (18-57)
Other LBSI, different level	12	1	13	65 (43-82)
Other LBSI, contralateral	6	1	7	35 (18-57)
Other LBSI, ipsilateral	10	1	11	55 (34-74)
Other LBSI, bilateral	2	0	2	10 (3-30)
Other LBSI, healed	12	2	14	70 (48-85)
Other LBSI, did not heal <sup>a</sup>	6	0	6	30 (15-52)

Note: <sup>a</sup>Cases with healing status unknown not included in data. Proportions calculated from total of known cases.

Table 2: Individual characteristics of injured and non-injured bowlers

Individual characteristics	Injured bowlers <sup>a</sup>			Non-injured bowlers <sup>a</sup>			Injured Vs All Non-injured <sup>b</sup>	
	All (n=43)	Male (n=33)	Female (n=10)	All (n=28)	Male (n=18)	Female (n=10)	Odds ratio (95% CI)	p
Age (years)	21.5 (19.8-25.4)	22.6 (19.8-25.7)	20.9 (18.1-22.3)	26.4 (22.3-30.0)	27.5 (23.0-30.0)	23.4 (21.6-29.0)	All: 0.85 (0.76-0.96) Male: 0.84 (0.72-0.97) Female: 0.83 (0.66-1.05)	All: 0.007 Male: 0.016 Female: 0.115
Height (cm)	190.5 (184.3-193.0)	192.0 (190.0-195.0)	174.3 (169.1-178.0)	185.2 (175.3-191.3)	187.5 (185.4-195.0)	173.1 (169.0-174.5)	All: 1.04 (0.99-1.09) Male: 1.08 (0.96-1.22) Female: 1.05 (0.89-1.23)	All: 0.146 Male: 0.176 Female: 0.575
Lower limb length (cm)	93.1 (87.9-96.3)	94.5 (93.0-97.4)	85.3 (81.9-86.4)	91.3 (85.9-94.0)	93.0 (91.5-96.0)	85.0 (82.9-86.1)	All: 1.03 (0.94-1.12) Male: 1.02 (0.88-1.18) Female: 1.02 (0.78-1.33)	All: 0.515 Male: 0.768 Female: 0.898
Weight (kg)	86.7 (78.0-92.9)	90.4 (85.5-95.7)	69.5 (66.1-74.0)	84.4 (76.6-92.7)	89.2 (83.3-94.4)	74.8 (66.0-77.0)	All: 1.02 (0.97-1.06) Male: 1.02 (0.94-1.11) Female: 0.97 (0.86-1.09)	All: 0.478 Male: 0.631 Female: 0.555

Note: <sup>a</sup>Descriptive data presented as median (interquartile range). <sup>b</sup>p-value compares injured vs all non-injured bowlers for each of the 3 groups: all, male, female.

Table 3: Musculoskeletal characteristics (trunk and lower limb) of injured and non-injured bowlers

Musculoskeletal variables	Injured bowlers <sup>a</sup>			Non-injured bowlers <sup>a</sup>			All Injured Vs All Non-Injured
	All (n=41)	Male (n=31)	Female (n=10)	All (n=28)	Male (n=18)	Female (n=10)	p
Ankle dorsiflexion (FF) (cm)	12 (11-13)	12 (11-14)	11 (11-12)	13 (11-15)	14 (10-16)	13 (12-15)	0.328
Ankle dorsiflexion (BF) (cm)	12 (11-14)	12 (11-14)	12 (12-13)	13 (10-15)	14 (11-17)	11 (9-14)	0.729
Star Excursion Balance Test total (FF) (cm)	106 (101-111)	106 (101-111)	106 (100-107)	107 (98-111)	108 (102-112)	100 (94-105)	0.806
Star Excursion Balance Test total (BF) (cm)	106 (101-112)	107 (102-112)	104 (99-107)	103 (98-111)	109 (98-112)	98 (96-101)	0.286
Lumbar lateral flexion (FF) (cm)	47 (44-50)	48 (46-52)	42 (40-47)	47 (46-50)	47 (47-50)	46 (45-48)	0.493
Lumbar lateral flexion (BF) (cm)	46 (43-50)	47 (44-51)	43 (41-46)	46 (45-48)	47 (45-49)	46 (45-47)	0.939
Trunk rotation (FF) (deg)	72 (70-80)	72 (70-80)	67 (55-75)	72 (65-90)	70 (62-90)	76 (71-84)	0.405
Trunk rotation (BF) (deg)	75 (65-80)	75 (70-80)	65 (64-76)	75 (66-90)	75 (60-90)	75 (71-83)	0.664
Modified Thomas hip extension (FF) (deg)	0 (-3-0)	0 (-1-0)	-1 (-4-0)	-1 (-4-0)	-2 (-3-0)	-1 (-3- -1)	0.515
Modified Thomas hip extension (BF) (deg)	0 (-2-0)	0 (-1-0)	-1 (-2-0)	-1 (-2-0)	0 (-2-0)	-1 (-2- -1)	0.988
Active knee extension (FF) (deg)	70 (63-77)	70 (62-77)	70 (65-76)	72 (66-80)	74 (69-78)	69 (59-80)	0.517
Active knee extension (BF) (deg)	70 (67-79)	70 (65-78)	80 (70-84)	72 (65-79)	72 (65-78)	72 (62-79)	0.724
Passive hip internal rotation in hip flexion (FF) (deg)	30 (26-37)	30 (23-37)	29 (27-36)	34 (28-45)	34 (23-45)	38 (33-45)	0.286
Passive hip internal rotation in hip flexion (BF) (deg)	28 (24-40)	27 (23-40)	37 (27-48)	32 (22-40)	26 (19-40)	34 (28-45)	0.806

Table 3 continued: Musculoskeletal characteristics (trunk and lower limb) of injured and non-injured bowlers

Musculoskeletal variables	Injured bowlers <sup>a</sup>			Non-injured bowlers <sup>a</sup>			All Injured Vs All Non-Injured
	All (n=41)	Male (n=31)	Female (n=10)	All (n=28)	Male (n=18)	Female (n=10)	<i>P</i>
Bent knee fall out (FF) (cm)	15 (15-19)	15 (14-19)	15 (15-18)	14 (11-17)	16 (14-17)	14 (10-15)	0.205
Bent knee fall out (BF) (cm)	15 (14-18)	15 (14-18)	15 (12-16)	14 (10-16)	14 (12-17)	13 (10-13)	0.153
Biering-Sorenson test (sec)	150 (120-180)	150 (129-180)	106 (97-125)	135 (119-180)	159 (105-180)	134 (122-158)	0.550
Hip abduction strength (FF) (N)	211 (174-253)	228 (211-266)	165 (143-169)	202 (169-231)	226 (204-237)	149 (149-171)	0.545
Hip abduction strength (BF) (N)	214 (185-246)	231 (206-255)	167 (158-171)	209 (183-237)	220 (200-244)	184 (140-187)	0.650
Hip adduction strength (FF) (N)	216 (184-249)	237 (210-268)	147 (134-154)	193 (158-231)	230 (203-262)	149 (138-176)	0.732
Hip adduction strength (BF) (N)	220 (180-244)	231 (215-261)	138 (132-156)	201 (158-239)	239 (202-259)	154 (149-158)	0.866
Groin squeeze strength (N)	312 (245-387)	352 (292-394)	233 (222-240)	279 (221-355)	334 (268-413)	224 (217-245)	0.406
Hip flexion strength (FF) (N)	383 (317-431)	409 (369-440)	269 (255-294)	367 (325-437)	418 (356-448)	323 (292-360)	0.985
Hip flexion strength (BF) (N)	378 (324-442)	418 (375-451)	264 (255-303)	365 (326-431)	400 (356-454)	325 (292-352)	Female: 0.100 0.464
Hip extension strength (FF) (N)	347 (290-391)	360 (321-405)	270 (235-333)	369 (305-406)	378 (334-415)	352 (277-379)	Female: 0.140 0.271
Hip extension strength (BF) (N)	343 (318-400)	388 (336-404)	290 (251-328)	369 (316-405)	375 (325-409)	352 (316-392)	Female: 0.097 0.568
Lumbopelvic control grade	4 (2-5)	4 (3-5)	2 (1-4)	3 (2-4)	4 (2-5)	2 (2-3)	Female: 0.095 0.411
Beighton Hypermobility Scale	0 (0-2)	0 (0-2)	0 (0-2)	1 (0-5)	0 (0-2)	3 (0-6)	0.068 Male: 0.440 Female: 0.119
Single leg hamstring bridge total (FF)	30 (22-30)	30 (24-30)	21 (17-30)	25 (21-30)	30 (25-30)	18 (13-21)	0.262
Single leg hamstring bridge total (BF)	30 (20-30)	30 (24-30)	21 (20-28)	24 (19-30)	20 (24-30)	18 (13-21)	0.168
Single leg decline squat (FF) (0-2)	2 (1-2)	2 (1-2)	2 (1-2)	2 (1-2)	2 (1-2)	2 (1-2)	0.516
Single leg decline squat (BF) (0-2)	2 (1-2)	2 (1-2)	2 (1-2)	1 (1-2)	1 (1-2)	1 (1-2)	0.407
Calf raises total (FF)	23 (20-25)	24 (20-25)	23 (22-26)	25 (21-25)	25 (25-25)	19 (17-25)	0.502
Calf raises total (BF)	25 (20-25)	24 (20-25)	25 (21-26)	25 (22-25)	25 (25-25)	22 (19-25)	0.293

Note: <sup>a</sup>Data presented as median (interquartile range). Abbreviations: BF = back foot, FF = front foot, N = newton.

Table 4: Bowling technique of injured and non-injured bowlers

Technique variables	Injured bowlers <sup>a</sup>			Non-injured bowlers <sup>a</sup>			All Injured Vs All Non-Injured
	All (n=25)	Male (n=21)	Female (n=4)	All (n=18)	Male (n=13)	Female (n=5)	<i>p</i>
Pelvis rotation (BFF) (deg)	235 (227-245)	235 (227-245)	235 (131-240)	231 (223-244)	230 (223-243)	243 (226-254)	0.613
Shoulder rotation (BFF) (deg)	219 (209-234)	214 (209-228)	235 (230-239)	219 (203-228)	221 (202-231)	210 (208-221)	0.535
Shoulder counter rotation (deg)	32 (22-41)	32 (26-46)	27 (19-34)	36 (23-45)	31 (23-47)	42 (32-42)	0.791
Lateral flexion (FFC) (deg)	172 (167-180)	171 (167-178)	184 (174-189)	176 (167-180)	175 (167-181)	180 (172-183)	0.810
Lateral flexion (BR) (deg)	149 (140-153)	146 (140-153)	155 (144-162)	146 (140-153)	146 (140-149)	152 (140-153)	0.951
Lateral flexion minimum (deg)	143 (136-148)	143 (137-146)	160 (142-162)	143 (136-150)	142 (136-147)	152 (137-153)	0.815
Hip/shoulder separation (BFF) (deg)	15 (7-24)	18 (13-25)	1 (-3-5)	18 (6-23)	18 (7-23)	N/A	0.752
Thoraco-pelvic extension (BFF) (deg)	174 (165-180)	172 (164-177)	178 (175-182)	172 (163-185)	171 (162-185)	172 (168-178)	0.703
Thoraco-pelvic extension (FFC) (deg)	190 (178-193)	187 (178-193)	192 (170-193)	185 (175-192)	181 (174-189)	194 (188-195)	0.156
Back knee angle (BFF) (deg)	135 (127-144)	135 (125-143)	139 (131-148)	139 (129-145)	139 (125-145)	137 (135-144)	0.860
Back knee angle minimum (deg)	116 (110-124)	122 (110-128)	111 (110-113)	117 (105-130)	119 (104-131)	N/A	0.533
Front knee angle (FFC) (deg)	169 (162-173)	167 (162-172)	175 (172-176)	167 (157-175)	166 (157-170)	176 (173-176)	0.240
Front knee angle (BR) (deg)	163 (131-178)	163 (131-172)	174 (159-182)	164 (144-178)	165 (136-177)	164 (163-173)	0.749
Front knee angle minimum (deg)	154 (132-163)	150 (132-163)	162 (146-172)	157 (134-164)	152 (130-165)	N/A	0.695
Ball speed maximum (km/h)	125 (116-132)	128 (124-132)	104 (101-105)	123 (109-127)	126 (122-128)	104 (99-108)	0.204 Male: 0.318 Female: 0.859

Note: <sup>a</sup>Data presented as median (interquartile range). Abbreviations: BFF = back foot flat, FFC = front foot contact, BR = ball release.

Table 5: Bowling frequency preceding injury of injured bowlers and end of season for non-injured bowlers

Bowling frequency variables	Injured bowlers <sup>a</sup>			Non-injured bowlers <sup>a</sup>			All Injured Vs All Non-Injured <sup>b</sup>
	All (n=43)	Male (n=33)	Female (n=10)	All (n=28)	Male (n=18)	Female (n=10)	<i>p</i>
Total balls previous 4 weeks	343 (219-457)	389 (234-503)	282 (54-357)	288 (143-550)	390 (302-591)	48 (0-156)	All: 0.992 Male: 0.119 Female: 0.039
Total days previous 4 weeks	10 (7-12)	10 (7-12)	9 (2-11)	5 (4-9)	9 (5-10)	2 (0-5)	All: 0.028 Male: 0.570 Female: 0.026
Total balls previous 12 weeks	1059 (700-1332)	1080 (702-1344)	846 (588-1144)	1220 (827-1673)	1543 (1212-1821)	755 (581-873)	All: 0.084 Male: 0.007 Female: 0.341
Total days previous 12 weeks	28 (19-35)	27 (23-35)	31 (19-35)	29 (22-33)	32 (28-37)	20 (18-25)	All: 0.860 Male: 0.092 Female: 0.074
Total balls previous 52 weeks	3542 (3170-4284)	3632 (3232-4358)	3384 (2678-3742)	4507 (3290-5849)	5383 (4945-5946)	3021 (2630-3419)	All: 0.024 Male: 0.001 Female: 0.477
Total days previous 52 weeks	97 (86-113)	96 (85-107)	106 (90-118)	106 (93-120)	115 (103-125)	95 (83-103)	All: 0.106 Male: 0.012 Female: 0.255

Note: <sup>a</sup>Data presented as median (interquartile range). <sup>b</sup>*p*-value compares all injured Vs all non-injured bowlers for each of the 3 groups: all, male, female.

Bowling frequency variables are presented in Table 5. Comparing male and female bowlers, male bowlers bowled more balls over the previous four ( $p = 0.005$ ), 12 ( $p = 0.005$ ), and 52 weeks ( $p = 0.021$ ). There was no difference in the number of days bowled over the previous four ( $p = 0.067$ ), 12 ( $p = 0.342$ ), and 52 weeks ( $p = 0.473$ ). Injured bowlers tended to bowl more days in the previous four weeks ( $p = 0.028$ ), and less balls in the previous 52 weeks ( $p = 0.024$ ). When separated by sex, injured female bowlers bowled more balls ( $p = 0.039$ ) and days ( $p = 0.026$ ) in the previous four weeks. Injured male bowlers bowled less balls in the previous 12 weeks ( $p = 0.007$ ), and less balls ( $p = 0.001$ ) and less days ( $p = 0.012$ ) in the previous 52 weeks. Due to the strong multicollinearity between bowling frequency variables, total days bowled in the previous four weeks was selected as the only bowling frequency variable to include in the multivariate analyses based upon previous research in a similar cohort (Kountouris et al., 2019).

Age, history of any LBSI previously, and total days bowled in the previous four weeks were included in multivariate analyses based upon lower  $p$ -values and previous research (summarised in the introduction). The best model included all three variables (Chi-square = 28.9,  $p < 0.001$ ). Younger age (odds ratio 0.73 [0.61–0.86],  $p < 0.001$ ), history of any LBSI previously (8.84 [2.08–37.59],  $p = 0.003$ ), and more days bowled in the previous four weeks (1.19 [1.03–1.38],  $p = 0.018$ ) were associated with an increased likelihood of injury. The model explained 45% of the variance (Nagelkerke R square) and correctly classified 79% of cases.

#### 4. Discussion

Lumbar bone stress injuries are a concern for fast bowlers, with the cost of injury including significant time off bowling (Frost & Chalmers, 2014; Orchard et al., 2016) and risk of subsequent injury (Cheung et al., 2018; Kountouris et al., 2018). Several risk factors have been purported in the literature (Alway et al., 2019a; Alway et al., 2020; Bayne et al., 2016; Dennis et al., 2005; Elliott et al., 1992; Foster et al., 1989; Kountouris et al., 2019; Orchard et al., 2015a; Portus et al., 2004), however their relative importance is unclear. This study addressed some limitations of previous research by conducting multifactorial analysis for a relatively large cohort of elite male and female fast bowlers over a four-year period to further understand the contribution of purported risk factors to LBSI.

History of any LBSI previously was the strongest factor associated with LBSI in elite fast bowlers, increasing the likelihood of injury by a factor of 3.94 (1.43–10.83) when considered independently, and 8.84 (2.08–37.59) when considered alongside age and total days bowled in the previous four weeks. This is the first time an association between previous and subsequent LBSI has been reported in cricket players. Systematic reviews of risk factors of non-contact injury in adolescent fast bowlers (Forrest et al., 2017) and lower back pain in fast bowlers (Morton et al., 2014) did not include previous stress fracture or bone stress injury. A history of stress fracture has been associated with increased risk of subsequent stress fracture in adolescent female athletes (Nose-Ogura et al., 2019) and runners (Wright et al., 2015), likely related to persistence of factors which contributed to the earlier injury contributing to the

subsequent injury (Beck & Drysdale, 2021). An additional factor resulting from the previous injury is that the bone mineral density may be lower at the previously injured site (Beck & Drysdale, 2021). Initial research in this area in elite fast bowlers suggests that bone mineral density of lumbar vertebrae may be lower for bowlers with a history of stress fracture, however further research is needed to elucidate whether this may be a cause or consequence of injury (Alway et al., 2019b). Resumption of bowling once there is no visible fracture line and bone marrow oedema has resolved (Singh et al., 2021) may be premature if bone mineral density has not been sufficiently restored.

Younger age was a strong factor associated with LBSI, with injured bowlers on average five years younger than non-injured bowlers (21.5 [19.8–25.4] vs 26.4 [22.3–20.0],  $p = 0.007$ ). This finding was irrespective of sex and is consistent with previous research which has found fast bowlers under 22 years of age are at three to four times the risk of a bone stress injury, most commonly involving the lumbar spine (Alway et al., 2019a; Blanch et al., 2015). Similarly, across other sports, younger athletes and those less skeletally mature have consistently been found to be at greater risk of LBSI (Blanch et al., 2015; Cyron & Hutton, 1978; Fournier et al., 1997; Fredrickson et al., 1984; Kim & Green, 2011; Micheli & Wood, 1995). These findings align with the theory of bone maturation, whereby peak bone mineral density of the lumbar spine does not occur until approximately 23 years of age in males (Xue et al., 2020), with increases of up to 10% in bone mineral content occurring after linear growth has ended (McCormack et al., 2017). Bone mineral density has been shown to positively adapt to the specific stresses of fast bowling (Alway et al., 2019b; Keylock et al., 2021). Therefore, it is important to consider other factors alongside age which may contribute to bone adaptation or maladaptation with fast bowling.

Bowling technique and musculoskeletal variables did not reveal any strong, consistent risk factors for LBSI. This may in part be attributed to a lack of precision in the measurement of lumbar motion using the current 3-D bowling biomechanical model. Recent refinements in the modelling of bowling technique separate lateral flexion between the thoracolumbar and lumbopelvic regions, with injured bowlers displaying larger lateral flexion (non-significant, medium effect) at the lumbopelvic junction (Alway et al., 2020). Musculoskeletal screening assessments are not well supported as indicators of injury risk (Bahr, 2016), like biomechanics screenings, they typically only provide a snapshot in time of a movement quality, range or muscle strength, often at a considerable time frame before an individual is injured. They also do not take into account the effect of fatigue on muscle strength and movement control. Although screening tests may not be good predictors of injury, they may still be useful in combination with biomechanical screening to provide individualised interpretation. For example, identifying ranges of available motion or muscle strength that may impact on a bowler's ability to efficiently transfer the momentum generated from their run up through the delivery stride and into the ball.

Bowling frequency analyses showed different patterns between male and female, injured and non-injured bowlers. Injured female bowlers had a higher bowling frequency in the previous four weeks compared to their non-injured counterparts. Conversely, injured male bowlers tended to have a lower bowling frequency in the previous 12- and 52-weeks compared to their

non-injured counterparts. These findings are inconsistent with previous research which has shown a higher bowling frequency in the 12 weeks preceding injury to be associated with LBSI in adolescent male fast bowlers (Kountouris et al., 2019; Sims et al., 2021) and adult male professional fast bowlers (Alway et al., 2019a; Orchard et al., 2015a). The findings of this study must be interpreted with caution, considering the potential inaccuracies of bowler-reported data and the inherent disparity between bowling frequencies taken from the day of injury diagnosis for injured bowlers and from the end of the season for non-injured bowlers. It is also important to note that bone stress develops over time and the date of diagnosis is not at a consistent stage of bone stress (Kountouris et al., 2018). For some bowlers this may mean that low level symptoms that did not trigger investigation and diagnosis may have led to modified bowling loads prior to diagnosis. An additional consideration is that non-injured bowlers were older and hence may have progressed to higher bowling loads.

The stringent criteria for the control group were intended to provide a true representation of 'non-injured' or 'resilient' bowlers. As such, it was not possible to match each individual injured bowler with a sex- and age-matched control which would have strengthened statistical analyses. Due to the relatively small number of female bowlers included in the study, comparison between injured and non-injured female bowlers is statistically underpowered. With ongoing monitoring, it will be possible to conduct follow-up research with a larger dataset to further understand the risk factors in female bowlers.

Ultimately, injury is an outcome of a complex system with multiple interacting layers of individual and ecological factors (Hulme & Finch, 2015). Collapsing the complex system down to a handful of routinely monitored variables, as in this study, has inherent limitations. A further limitation is the use of statistics evaluating a linear relationship, when the relationship between factors and injury is likely non-linear (Bittencourt et al., 2016). Future research with a larger, international dataset may lend to more complex analyses to identify patterns of factors which increase injury risk. Another direction for future research is to focus more specifically on the bone structure and tissue capacity of the lumbar vertebrae.

The overarching finding of this study is that history of any LBSI previously, younger age, and higher bowling frequency in the previous four weeks explain approximately 45% of LBSI risk in elite fast bowlers. The remaining 55% is not explained by any individual, musculoskeletal, or technique variables across all bowlers. All variables logically contribute to injury risk, yet their interaction is likely unique and changes over time. A primary goal for injury prevention should be to reduce the risk of a bowler sustaining a LBSI by taking into consideration any history of LBSI and the age of the bowler when prescribing bowling frequency. This will require coaches, parents, and young bowlers to work together to monitor and manage bowling frequency to an appropriate level for the developing vertebrae, gradually increasing bowling frequency as the musculoskeletal system develops and adapts to the specific demands of bowling. Bowling frequency cannot be universally prescribed; however this study and previous research suggests 1–3 days between bowling days allows the tissue to recover from the stress of bowling (Dennis et al., 2005; Kountouris et al., 2018; Orchard et al., 2015a). An individualised and adaptive approach to fast bowler preparation JSES | <https://doi.org/10.36905/jses.2022.03.06>

may also address other factors such as musculoskeletal characteristics or bowling technique if deemed relevant to the individual at the time. An additional tool in the management of more elite fast bowlers, if feasible, is to incorporate routine imaging to detect pre-symptomatic bone stress and indicate the need for de-loading of the tissue to prevent progression to a more severe LBSI (Kountouris et al., 2018; Kountouris et al., 2019; Sims et al., 2019).

### Conflict of Interest

The authors declare no conflict of interests.

### Acknowledgment

This research was supported in-kind by Cricket Australia. We acknowledge the sport science and sport medicine staff from State and Territory Cricket Associations and Cricket Australia who consistently measured and recorded data over the years to enable this research.

### References

- Alway, P., Brooke-Wavell, K., Langley, B., King, M., & Peirce, N. (2019a). Incidence and prevalence of lumbar stress fracture in English County Cricket fast bowlers, association with bowling workload and seasonal variation. *BMJ Open Sport and Exercise Medicine*, 5(1), e000529.
- Alway, P., Felton, P., Brooke-Wavell, K., Peirce, N., & King, M. (2020). Cricket fast bowling technique and lumbar bone stress injury. *Medicine and Science in Sports and Exercise*, 53(3), 581-589. <https://doi.org/10.1249/mss.0000000000002512>
- Alway, P., Peirce, N., King, M., Jardine, R., & Brooke-Wavell, K. (2019b). Lumbar bone mineral asymmetry in elite cricket fast bowlers. *Bone*, 127, 537-543.
- Bahr, R. (2016). Why screening tests to predict injury do not work—and probably never will...: a critical review. *British Journal of Sports Medicine*, 50(13), 776-780. <https://doi.org/10.1136/bjsports-2016-096256>
- Baker, R. (2001). Pelvic angles: a mathematically rigorous definition which is consistent with a conventional clinical understanding of the terms. *Gait and Posture*, 13(1), 1-6.
- Bayne, H., Elliott, B., Campbell, A., & Alderson, J. (2016). Lumbar load in adolescent fast bowlers: A prospective injury study. *Journal of Science and Medicine in Sport*, 19(2), 117-122. <https://doi.org/10.1016/j.jsams.2015.02.011>
- Beck, B., & Drysdale, L. (2021). Risk factors, diagnosis and management of bone stress injuries in adolescent athletes: A narrative review. *Sports*, 9(4), 52. <https://doi.org/10.3390/sports9040052>
- Biering-Sorensen, F. (1984). Physical measurements as risk indicators for low-back trouble over a one-year period. *Spine*, 9(2), 106-119.
- Bittencourt, N. F., Meeuwisse, W., Mendonça, L., Nettel-Aguirre, A., Ocarino, J., & Fonseca, S. (2016). Complex systems approach for sports injuries: moving from risk factor identification to injury pattern recognition—narrative review and new concept. *British Journal of Sports Medicine*, 50(21), 1309-1314.

- Blanch, P., Orchard, J., Kountouris, A., Sims, K., & Beakley, D. (2015). Different tissue type categories of overuse injuries to cricket fast bowlers have different severity and incidence which varies with age. *South African Journal of Sports Medicine*, 27(4), 108-113. <https://doi.org/10.17159/2078-516x/2015/v27i4a436>
- Cheung, K. K., Dhawan, R. T., Wilson, L. F., Peirce, N. S., & Rajeswaran, G. (2018). Pars interarticularis injury in elite athletes: The role of imaging in diagnosis and management. *European Journal of Radiology*, 108, 28-42.
- Cyron, B., & Hutton, W. (1978). The fatigue strength of the lumbar neural arch in spondylolysis. *Journal of Bone and Joint Surgery, British Volume*, 60-B(2), 234-238.
- Delahunt, E., Kennelly, C., McEntee, B. L., Coughlan, G. F., & Green, B. S. (2011). The thigh adductor squeeze test: 45 of hip flexion as the optimal test position for eliciting adductor muscle activity and maximum pressure values. *Manual Therapy*, 16(5), 476-480.
- Dennis, R. J., Finch, C. F., & Farhart, P. J. (2005). Is bowling workload a risk factor for injury to Australian junior cricket fast bowlers? *British Journal of Sports Medicine*, 39(11), 843-846. <https://doi.org/10.1136/bjism.2005.018515>
- Dennis, R. J., Finch, C. F., McIntosh, A. S., & Elliott, B. C. (2008). Use of field-based tests to identify risk factors for injury to fast bowlers in cricket. *British Journal of Sports Medicine*, 42(6), 477-482.
- Elliott, B. C., Hardcastle, P. H., Burnett, A. E., & Foster, D. H. (1992). The influence of fast bowling and physical factors on radiologic features in high performance young fast bowlers. *Sports Medicine, Training and Rehabilitation*, 3(2), 113-130. <https://doi.org/10.1080/15438629209517008>
- Farfan, H., Osteria, V., & Lamy, C. (1976). The mechanical etiology of spondylolysis and spondylolisthesis. *Clinical Orthopaedics and Related Research*, 117, 40-55.
- Felton, P. J., Lister, S. L., Worthington, P. J., & King, M. A. (2019). Comparison of biomechanical characteristics between male and female elite fast bowlers. *Journal of Sports Sciences*, 37(6), 665-670. <https://doi.org/10.1080/02640414.2018.1522700>
- Forrest, M. R., Hebert, J. J., Scott, B. R., Brini, S., & Dempsey, A. R. (2017). Risk factors for non-contact injury in adolescent cricket pace bowlers: a systematic review. *Sports Medicine*, 47(12), 2603-2619.
- Foster, D., John, D., Elliott, B., Ackland, T., & Fitch, K. (1989). Back injuries to fast bowlers in cricket: A prospective study. *British Journal of Sports Medicine*, 23(3), 150-154. <https://doi.org/10.1136/bjism.23.3.150>
- Fournier, P.-E., Rizzoli, R., Slosman, D.-O., Theintz, G., & Bonjour, J.-P. (1997). Asynchrony between the rates of standing height gain and bone mass accumulation during puberty. *Osteoporosis International*, 7(6), 525-532. <https://doi.org/10.1007/bf02652557>
- Freckleton, G., Cook, J., & Pizzari, T. (2014). The predictive validity of a single leg bridge test for hamstring injuries in Australian Rules Football Players. *British Journal of Sports Medicine*, 48(8), 713-717.
- Fredrickson, B., Baicer, D., McHolick, W., Yuan, H., & Lubicky, J. (1984). The natural history of spondylolysis and spondylolisthesis. *The Journal of Bone and Joint Surgery - American Volume*, 66A(5), 699-707.
- Frost, W. L., & Chalmers, D. J. (2014). Injury in elite New Zealand cricketers 2002-2008: descriptive epidemiology. *British Journal of Sports Medicine*, 48(12), 1002-1007. <https://doi.org/10.1136/bjsports-2012-091337>
- Goggins, L., Peirce, N., Ranson, C., McCaig, S., Newman, D., Langley, B., . . . Stokes, K. (2020). Injuries in England and Wales elite men's domestic cricket: A nine season review from 2010 to 2018. *Journal of Science and Medicine in Sport*, 23(9), 836-840.
- Hertel, J., Braham, R. A., Hale, S. A., & Olmsted-Kramer, L. C. (2006). Simplifying the star excursion balance test: analyses of subjects with and without chronic ankle instability. *Journal of Orthopaedic and Sports Physical Therapy*, 36(3), 131-137.
- Hulme, A., & Finch, C. F. (2015). From monocausality to systems thinking: a complementary and alternative conceptual approach for better understanding the development and prevention of sports injury. *Injury epidemiology*, 2(1), 1-12.
- Jacobs, J., Olivier, B., Dawood, M., & NK, P. P. (2021). Prevalence and incidence of injuries among female cricket players: a systematic review and meta-analyses. *JBI Evidence Synthesis*, 19(8), 1977-1983. <https://doi.org/10.11124/jbies-21-00120>
- Johnson, K. D., & Grindstaff, T. L. (2010). Thoracic rotation measurement techniques: clinical commentary. *North American Journal of Sports Physical Therapy*, 5(4), 252-256.
- Johnson, M., Ferreira, M., & Hush, J. (2012). Lumbar vertebral stress injuries in fast bowlers: A review of prevalence and risk factors. *Physical Therapy in Sport*, 13(1), 45-52. <https://doi.org/10.1016/j.ptsp.2011.01.002>
- Kendall, F. P., McCreary, E. K., & Provance, P. G. (1993). *Muscles, testing and function: with posture and pain: Williams & Wilkins.*
- Keylock, L., Felton, P., Alway, P., Brooke-Wavell, K., Peirce, N., & King, M. (2021). Lumbar bone mineral adaptation: The effect of fast bowling technique in adolescent cricketers. *Medicine and Science in Sports and Exercise*, 54(3), 438-446. <https://doi.org/10.1249/mss.0000000000002820>
- Kim, H. J., & Green, D. W. (2011). Spondylolysis in the adolescent athlete. *Current Opinion in Pediatrics*, 23(1), 68-72.
- Kountouris, A., Saw, R., & Saw, A. (2018). Management of lumbar spondylolysis in athletes: Role of imaging. *Current Radiology Reports*, 6(10), 39. <https://doi.org/10.1007/s40134-018-0299-z>
- Kountouris, A., Sims, K., Beakley, D., Saw, A. E., Orchard, J., Rotstein, A., & Cook, J. L. (2019). MRI bone marrow oedema precedes lumbar bone stress injury diagnosis in junior elite cricket fast bowlers. *British Journal of Sports Medicine*, 53, 1236-1239. <https://doi.org/10.1136/bjsports-2017-097930>
- Malliaras, P., Hogan, A., Nawrocki, A., Crossley, K., & Schache, A. (2009). Hip flexibility and strength measures: reliability and association with athletic groin pain. *British Journal of Sports Medicine*, 43(10), 739-744.
- McCormack, S. E., Cousminer, D. L., Chesi, A., Mitchell, J. A., Roy, S. M., Kalkwarf, H. J., . . . Shepherd, J. A. (2017). Association between linear growth and bone accrual in a diverse cohort of children and adolescents. *JAMA pediatrics*, 171(9), e171769-e171769.
- Micheli, L. J., & Wood, R. (1995). Back pain in young athletes: Significant differences from adults in causes and patterns.

- Archives of Pediatrics and Adolescent Medicine*, 149(1), 15-18.
- Mills, J. D., Taunton, J. E., & Mills, W. A. (2005). The effect of a 10-week training regimen on lumbo-pelvic stability and athletic performance in female athletes: A randomized-controlled trial. *Physical Therapy in Sport*, 6(2), 60-66.
- Morton, S., Barton, C. J., Rice, S., & Morrissey, D. (2014). Risk factors and successful interventions for cricket-related low back pain: a systematic review. *British Journal of Sports Medicine*, 48(8), 685-691.
- Nealon, A. R., & Cook, J. L. (2018). Trunk side strain has a high incidence in first-class cricket fast bowlers in Australia and England. *Clinical Journal of Sport Medicine*, 28(3), 284-288.
- Nose-Ogura, S., Yoshino, O., Dohi, M., Kigawa, M., Harada, M., Hiraike, O., . . . Saito, S. (2019). Risk factors of stress fractures due to the female athlete triad: Differences in teens and twenties. *Scandinavian Journal of Medicine and Science in Sports*, 29(10), 1501-1510. <https://doi.org/10.1111/sms.13464>
- Nussbaumer, S., Leunig, M., Glatthorn, J. F., Stauffacher, S., Gerber, H., & Maffiuletti, N. A. (2010). Validity and test-retest reliability of manual goniometers for measuring passive hip range of motion in femoroacetabular impingement patients. *BMC Musculoskeletal Disorders*, 11(1), 1-11.
- Orchard, J. W., Blanch, P., Paoloni, J., Kountouris, A., Sims, K., Orchard, J. J., & Brukner, P. (2015a). Cricket fast bowling workload patterns as risk factors for tendon, muscle, bone and joint injuries. *British Journal of Sports Medicine*, 49(16), 1064-1068. <https://doi.org/10.1136/bjsports-2014-093683>
- Orchard, J. W., Blanch, P., Paoloni, J., Kountouris, A., Sims, K., Orchard, J. J., & Brukner, P. (2015b). Fast bowling match workloads over 5–26 days and risk of injury in the following month. *Journal of Science and Medicine in Sport*, 18(1), 26-30. <https://doi.org/10.1016/j.jsams.2014.09.002>
- Orchard, J. W., James, T., Portus, M., Kountouris, A., & Dennis, R. (2009). Fast bowlers in cricket demonstrate up to 3- to 4-week delay between high workloads and increased risk of injury. *American Journal of Sports Medicine*, 37(6), 1186-1192. <https://doi.org/10.1177/0363546509332430>
- Orchard, J. W., Kountouris, A., & Sims, K. (2016). Incidence and prevalence of elite male cricket injuries using updated consensus definitions. *Open Access Journal of Sports Medicine*, 7, 187-194. <https://doi.org/10.2147/OAJSM.S117497>
- Perera, N. K. P., Kountouris, A., Kemp, J. L., Joseph, C., & Finch, C. F. (2019). The incidence, prevalence, nature, severity and mechanisms of injury in elite female cricketers: A prospective cohort study. *Journal of Science and Medicine in Sport*, 22(9), 1014-1020.
- Portus, M. R., Mason, B. R., Elliott, B. C., Pfitzner, M. C., & Done, R. P. (2004). Technique factors related to ball release speed and trunk injuries in high performance Cricket fast bowlers. *Sports Biomechanics*, 3(2), 263-284. <https://doi.org/10.1080/14763140408522845>
- Ranson, C. A., Burnett, A. F., King, M., Patel, N., & O'Sullivan, P. B. (2008). The relationship between bowling action classification and three-dimensional lower trunk motion in fast bowlers in cricket. *Journal of Sports Sciences*, 26(3), 267-276. <https://doi.org/10.1080/02640410701501671>
- Robling, A. G., Castillo, A. B., & Turner, C. H. (2006). Biomechanical and molecular regulation of bone remodeling. *Annual Review of Biomedical Engineering*, 8(1), 455-498. <https://doi.org/10.1146/annurev.bioeng.8.061505.095721>
- Schache, A. G., Baker, R., & Lamoreux, L. W. (2006). Defining the knee joint flexion–extension axis for purposes of quantitative gait analysis: an evaluation of methods. *Gait and Posture*, 24(1), 100-109.
- Sims, K., Kountouris, A., Stegeman, J. R., Rotstein, A. H., Beakley, D., Saw, A. E., & Cook, J. L. (2019). MRI bone marrow oedema signal intensity: A reliable and valid measure of lumbar bone stress injury in elite junior fast bowlers. *Spine*, 45(18), e1166-e1177. <https://doi.org/10.1097/BRS.0000000000003277>
- Sims, K., Saw, R., Saw, A. E., Kountouris, A., & Orchard, J. W. (2021). Multiple risk factors associated with lumbar bone stress injury in youth cricket fast bowlers. *Journal of Sport and Exercise Science*, 5(2), 92-100. <https://doi.org/10.36905/jses.2021.02.01>
- Singh, S. P., Rotstein, A. H., Saw, A. E., Saw, R., Kountouris, A., & James, T. (2021). Radiological healing of lumbar spine stress fractures in elite cricket fast bowlers. *Journal of Science and Medicine in Sport*, 24(2), 112-115. <https://doi.org/10.1016/j.jsams.2020.06.018>
- Smits-Engelsman, B., Klerks, M., & Kirby, A. (2011). Beighton score: a valid measure for generalized hypermobility in children. *Journal of Pediatrics*, 158(1), 119-123. e114.
- Stuelcken, M., Pyne, D., & Sinclair, P. (2007). Anthropometric characteristics of elite cricket fast bowlers. *Journal of Sports Sciences*, 25(14), 1587-1597.
- Thorborg, K., Bandholm, T., Petersen, J., Weeke, K. Ø., Weinold, C., Andersen, B., . . . Hölmich, P. (2010). Hip abduction strength training in the clinical setting: with or without external loading? *Scandinavian Journal of Medicine and Science in Sports*, 20, 70-77.
- Wells, D., Dols, A., Donnelly, C. J., & Alderson, J. (2015). An examination of ball release determination methods in cricket bowling and its influence on bowling legality. Paper presented at the proceedings of the 5th World Congress of Science & Medicine in Cricket. Sydney, Australia.
- Worthington, P. J., King, M. A., & Ranson, C. A. (2013). Relationships between fast bowling technique and ball release speed in cricket. *Journal of Applied Biomechanics*, 29(1), 78-84. <https://doi.org/10.1123/jab.29.1.78>
- Wright, A. A., Taylor, J. B., Ford, K. R., Siska, L., & Smoliga, J. M. (2015). Risk factors associated with lower extremity stress fractures in runners: a systematic review with meta-analysis. *British Journal of Sports Medicine*, 49(23), 1517-1523.
- Xue, S., Kemal, O., Lu, M., Lix, L. M., Leslie, W. D., & Yang, S. (2020). Age at attainment of peak bone mineral density and its associated factors: The National Health and Nutrition Examination Survey 2005–2014. *Bone*, 131, 115163.

Supplementary Table 1: Musculoskeletal screening tests

<b>Musculoskeletal test</b>	<b>Procedure</b>
Ankle dorsiflexion	Foot positioned on tape measure with zero mark at the wall. Athlete lunges forward, keeping heel on ground, until knee touches the wall (Dennis et al., 2008).
Star Excursion Balance Test	Modified procedure as described by Hertel et al. (2006) measuring distance reached by one limb in the anterior, postero-medial and postero-lateral directions while maintaining single leg balance on the contra-lateral limb.
Lumbar lateral flexion	Athlete stands side on to wall with lateral hip in contact with wall and shoulder nearest wall abducted/elbow flexed. Athlete laterally flexes away from wall and distance to floor from fingertips is measured (Nealon & Cook, 2018).
Trunk rotation	Athlete sitting with stick held across front of shoulders. Trunk rotation measured with goniometer arms aligned with stick and starting position (modified from Johnson & Grindstaff, 2010)
Modified Thomas hip extension	Athlete supine on plinth with knees hanging free, flexes contralateral hip to chest and inclinometer used to measure the range of hip extension on ipsilateral hip (modified from Kendall et al., 1993).
Active knee extension	Athlete supine on bed maintains ipsilateral hip in 90 degrees hip flex with contralateral resting on bed. Athlete extends ipsilateral knee to end range and measured with inclinometer (Dennis et al., 2008).
Passive hip internal rotation in hip flexion	Athlete supine with hip flexed to 90 degrees. Range of internal rotation measured with long arm goniometer (Nussbaumer et al., 2010).
Bent knee fall out	Athlete supine with hips flexed to 45 degrees. Both hips passively abducted and externally rotated keeping feet together. Distance from fibular head to bed measured with tape measure (Malliaras et al., 2009).
Biering-Sorenson test	Athlete lies prone with trunk off edge of bed and lower body secured. Length of time trunk can be maintained horizontal is measured (Biering-Sorensen, 1984).
Hip abduction and adduction strength	Athlete supine on plinth. Hip abduction and adduction resisted and measured with handheld dynamometer (Thorborg et al., 2010).
Groin squeeze strength	Athlete lies supine on the bed in the crook lying position (hips flexed to 45°, knees flexed to 90°). Maximum adduction/squeeze effort measured with handheld dynamometer (Delahunt et al., 2011).
Hip flexion and extension strength	Athlete lies prone (hip extension) or sits on edge of plinth (hip flexion) and manual resistance applied and measured with hand held dynamometer (Thorborg et al., 2010).
Lumbopelvic control	Athlete lies supine with knees bent to 45 degrees and posteriorly tilts pelvis to lightly flatten lumbar spine onto bed. Progressive leg loading is then performed to the point where the athlete is unable to maintain the lumbar spine in contact with the bed (modified from (Mills et al., 2005)).
Beighton Hypermobility Scale	A series of limb and trunk movements evaluated for excessive mobility as previously described (Smits-Engelsman et al., 2011).
Single leg hamstring bridge	Athlete lies supine with foot on 60 cm high step with knee flexed to approximately 20 degrees. Contralateral hip is maintained in 90 degrees hip flexion and the number of hamstring bridges is recorded (Freckleton et al., 2014).
Single leg decline squat	Athlete stands on one leg on a decline board with arms folded across chest and the non-weight bearing knee in 90 degrees flexion with the hip in neutral. The athlete performs a single leg squat to 90 degrees of knee flexion. From an anterior view the examiner makes a subjective evaluation of the amount of femoral adduction and rates it either normal or excessive. From a posterior view the examiner makes a subjective judgement on whether the athlete maintains the trunk and pelvis in a level position (normal) or if there is excessive motion of these regions (modified from Bayne et al., 2016).
Calf raises	Athlete performs repeated single leg heel raises at a frequency of 25 raises per minute to a maximum of 25 repetitions (modified from Dennis et al., 2008)