Sprint Running with Lower-Limb Wearable Resistance: Acute Mechanical Responses and Training Outcomes

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Abstract

Sprint running, and in particular one's ability to perform maximal acceleration over short distances, is a key component of performance for many sports. Thus, the best methods to develop an athlete's sprint running capabilities is of interest to many coaches. Lower-limb wearable resistance (WR) is a movement- and speed-specific training method for sprint running that allows close adherence to the principle of training specificity. Therefore, lower-limb WR could be well suited for producing adaptations that transfer to unloaded sprint running. This thesis aimed to answer the overarching question, "What are the effects of lower-limb WR on short distance sprint running?"

A review of the literature (Chapter 2) found that lower-limb WR loading schemes of 0.6–5% body mass (BM) significantly increased contact time (2.9–8.9%), decreased step frequency (−1.4 to −3.7%), and slowed total sprint times (0.6–7.4%). However, minimal kinetic and joint kinematic information had been published which limited the understanding of the underlying mechanics associated with sprint running with lower-limb WR. Also, no prior investigations had employed a shank- or thigh-only load configuration. Further, there was no research-based evidence detailing how an athlete population might respond to lower-limb wearable resistance training (WRT) for sprint running. These important gaps and limitations provided a framework for the research undertaken in this thesis.

The first study (Chapter 3) investigated the effects of 2% BM thigh and shank WR on joint kinematics during early acceleration. It was found that significant differences in maximal joint angles between loaded and unloaded sprint running were small (ES = 0.23–0.38), limited to the hip and knee joints, and < 2° on average. Also, average hip flexion and extension velocity were significantly overloaded with the thigh and shank WR, which suggested a specific application for lower-limb WR to target the hip flexion and extension actions associated with fast sprint running. In study two (Chapter 4), it was found that athletes were largely able to maintain propulsive and net anterior-posterior impulse values using 2% BM thigh and shank WR. However, greater increases to braking and vertical impulses were observed with shank WR (2.72–26.3% compared to unloaded) than with thigh WR (2.17–12.1% compared to unloaded). Considering these findings and the greater practitioner interest in shank WR for training applications due to practical utility, a third study (Chapter 5) was undertaken to compare the force waveforms between unloaded and 2% BM shank WR sprint running to better understand the underlying cause(s) for increased horizontal braking and vertical impulses and determine if there are significant differences in the magnitude of forces around impact. Significant differences in the anterior-posterior component of the ground reaction force (i.e. greater levels of braking force) between unloaded and shank WR occurred between 20.8–28.3% of ground contact at 10 m, 20 m, and 30 m. Thus, there was no indication that greater horizontal braking or vertical forces occur during the impact portion of ground contact. These studies identified the

specific underlying mechanisms that may render thigh and shank WR as effective training tools for sprint acceleration performance.

Two training studies were subsequently undertaken in this thesis to investigate the longitudinal effects of shank WRT for sprint running in field-based sports athletes. Six weeks of WRT was found to be superior to unloaded training in maintaining the technical ability to produce horizontal force at low velocities and maintaining a horizontally oriented ground reaction force with increasing speed in collegiate/semi-professional rugby athletes (Chapter 6). Nine weeks of WRT in high school American football athletes did not result in significant post-training differences between the WR and unloaded training (Chapter 8). Detailed inspection of the training protocols employed and athlete responses provided evidence that shank-placed WR can be used to amplify the nuances of a sprint running training protocol.

Prior to Chapter 8, a study was completed to establish the level of agreement between the horizontal F-v profile variables obtained from two field-based velocity measurement devices, a 1080 Sprint and a Stalker ATS II radar gun (Chapter 7). This provided the necessary information to determine if the two devices could be used interchangeably to inform device selection, and thus, number of testing time points to be included in the training study that followed (Chapter 8).

The research presented in this thesis has identified the mechanical determinants that are overloaded by lower-limb WR, and thus, may be influenced over time to produce positive speed adaptations. Also, this thesis has identified lower-limb WRT as a time-efficient method to retain mechanical characteristics of sprint performance, which may have beneficial implications for sports with constrained schedules. In conclusion, it is suggested that this method of resistance training could be used concurrently with other resistance training methods in a mixed-method training approach to provide a unique stimulus to encourage continued improvement in speed development or further target velocity-based individual weaknesses.

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Attestation of Authorship

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

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Erin Harper Feser

Publications and Presentations

The publications listed below are a result of the research conducted in fulfilment of the degree of Doctor of Philosophy.

<u>Published Manuscripts</u>

Chapter 2 — Feser EH, Macadam P, Cronin JB. The effects of lower limb wearable resistance on sprint running performance: A systematic review. *Eur J Sports Sci*. 2020;20(3):394-406.
(Feser 85%, Macadam 10%, Cronin 5%)

Chapter 4 — Feser EH, Bezodis N, Neville J, Macadam P, Uthoff AM, Nagahara R, Tinwala F, Clark K, Cronin JB. Changes to horizontal force-velocity and impulse measures during sprint running acceleration with thigh and shank wearable resistance. [published online ahead of print, 2021 Feb 14]. *J Sports Sci*. 2021;1-9. doi: 10.1080/02640414.2021.1882771.
(Feser 80%, Bezodis 4%, Neville 4%, Macadam 2%, Uthoff 2%, Nagahara 2%, Tinwala 2%, Clark 2%, and Cronin 2%)

Chapter 5 — Feser EH, Neville J, Bezodis N, Macadam P, Uthoff AM, Nagahara R, Tinwala F, and Cronin JB. Waveform analysis of shank loaded wearable resistance during sprint running acceleration. [published online ahead of print, 2021 Apr 18]. *J Sports Sci*. 2021;1-8. doi: 10.1080/02640414.2021.1912966.
(Feser 82%, Neville 5%, Bezodis 3%, Macadam 2%, Uthoff 2%, Nagahara 2%, Tinwala 2%, and Cronin 2%)

Chapter 6 — Feser EH, Bayne H, Loubser I, Bezodis NE, Cronin JB. Wearable resistance sprint running is superior to training with no load for retaining performance in pre-season training for rugby athletes [published online ahead of print, 2020 Aug 17]. *Eur J Sports Sci.* 2020;1-9. doi.org/10.1080/17461391.2020.1802516
(Feser 82%, Bayne 7%, Loubser 7%, Bezodis 2%, Cronin 2%)

Chapter 8 — Feser EH, Korfist C, Lindley K, Bezodis N, Clark K, Cronin JB. The effects of lower-limb wearable resistance on sprint performance in high school American football athletes: A nine-week training study. [published online ahead of print, 2021 Mar 22]. *Int J Sports Sci Coach*. 2021;1-9. https://doi.org/10.1177%2F17479541211003403
(Feser 82%, Korfist 7%, Lindley 5%, Bezodis 2%, Clark 2%, Cronin 2%)

Manuscripts Under Review

Chapter 3 Feser EH, Neville J, Wells D, Diewald S, Bezodis N, Clark K, Nagahara R, Kameda M, Macadam P, Uthoff AM, Tinwala T, and Cronin JB. Lower-limb wearable resistance overloads joint angular velocity during early acceleration sprint running. *Eur J Sports Sci*. (under review).
(Feser 80%, Neville 4%, Wells 3%, Diewald 2%, Bezodis 2%, Clark 2%, Nagahara 1%, Kameda 1%, Macadam 1%, Uthoff 1%, Tinwala 1%, and Cronin 2%)

Chapter 7 Feser EH, Lindley K, Clark K, Bezodis N, Korfist C, Cronin JB. Comparison of the 1080 Sprint to radar for obtaining horizontal force-velocity profile variables during sprint running. *Int J Sports Sci Coach*. (under review).
(Feser 82%, Lindley 6%, Clark 4%, Bezodis 4%, Korfist 2%, Cronin 2%)

Conference Proceedings

Feser E, Macadam P, Nagahara R, Cronin J. The effects of lower limb wearable resistance on step kinematics during sprint running. 36th International Conference of Biomechanics in Sports; 2018; Auckland, New Zealand.
(Feser 90%, Macadam 4%, Nagahara 3%, Cronin 3%)

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

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Chapter 1. Introduction

1.1 Background

Sprint running, and in particular one's ability to perform maximal acceleration over short distances, is a key component of performance for many sports. The competitive advantage of being a faster athlete is obvious during a running race, but there is also evidence that highlights the importance of sprint running during team sports gameplay. For example, linear sprints have been identified as the most dominant offensive action in elite football [33] and 24% of game movements involve sprint running for rugby backs [32]; sprint running performance has been shown to differentiate between lower- and higher-level athletes in football [24]; and sprint running ability remains a centrepiece for many athlete scouting combines such as the 40-yard dash used by the National Football League in the United States. These factors emphasise the necessity of training an athlete's sprint running capabilities and, therefore, the best methods to develop an athlete's sprint running capabilities are of interest to many coaches.

1.1.1 Resistance Training Transference

Previously researchers have investigated resistance training programmes that utilised traditional gym-based strength and power training protocols, and their effectiveness to change sprint running performance. These programmes intend to improve the athletes' force and power production abilities under the assumption that general strength and power is directly influential to speed production, and therefore, any improvements resulting from the training programme should positively transfer to sprint running ability. While a requisite level of strength is necessary to produce the high levels of force compulsory to sprint running and should be maintained by continued training to avoid loss [42], training methods specific to sprint running (e.g. resisted sprint running) are more effective for improving short distance sprint running than nonspecific methods (i.e. strength, power, and plyometric training) [92]. One challenge that likely limits the transfer of nonspecific strength and power adaptation achieved with traditional gym-based strength and power training protocols to sprint running is the lack of specificity between the speed of the nonspecific training movement and the speed of the sprint running movement pattern.

During sprint running, muscular force production is constrained by short ground contact times and the need to rapidly reposition the limbs prior to next ground contact. This requires the athlete to be able to produce maximal levels of force under high muscular contraction speeds and short ground contact times. With resistance training, there is evidence to support a velocity specific effect, meaning strength improvements following resistance training are greatest at or near the velocity at which the training was performed [4]. Thus, speed-specific resistance training methods should be more effective in developing sprint-specific speed and power by influencing the athlete's ability to generate force at high contraction speeds.

Typically, sprint running specific resistance training methods involve introducing an external resistance in which the athlete must push or pull (e.g. weighted sled or resistance band) or move with (e.g. weighted vest) while completing the sprint running motion. These methods have been found to increase sprinting speed in response to training but it appears they are no more effective than sprint training with no external resistance [1,46]. More recent studies have further confirmed these findings [13,40,67,89]. One challenge that may limit the transference of these resisted sprint training methods is related to the general nature in how the resistance is applied. These methods require the athlete to move against a load that is predominantly applied near the athlete's centre of mass in only the vertical (e.g. vest loading) or horizontal (e.g. sled towing) direction. This, therefore, limits a systematic application of loading the sprint running movement pattern itself.

Clearly, science has yet to well elucidate how resistance training can be used to improve sprint running performance. Finding a resistance training method that allows the athlete to move at or close to sprint running specific speeds while providing a means to overload to the sprint running movement pattern directly, may be better suited for producing adaptations that transfer to unloaded sprint running. If so, this method of resistance training could be used concurrently with maximal strength training in a mixed-method training approach to further target velocity-based individual weaknesses and provide a unique stimulus to encourage continued improvement in speed development for high-level athletes that may have experienced a performance plateau.

1.1.2 Limb Inertial Manipulation as a Resistance Training Method

A training method that has the potential to circumvent the transference issues and loading limitations of current resistance training methods for sprint running is lower-limb WR. Lower-limb WR involves attaching external resistance to the lower-limbs of the athlete. The loading schemes are considered very light (i.e. ≤ 5% body mass) compared to traditional resistance training, which allows the athlete to perform sport-specific movements while loaded with minimal impact to movement speed alongside minimal/non-significant disruption to movement kinematics [54], thus allowing for better alignment to the principle of training specificity. Lower-limb WR is a form of rotational inertial manipulation and it has been shown that very light loading of the lower-limbs during running increases the mechanical work needed to perform the movement task, e.g. 0.50 kg attached to the thigh increased mechanical work done on the thigh by 9.5% [65]. These changes have been attributed to the increases in mechanical work required by the musculature, in particular that of the hip joint, to move the added limb load [65,66]. These findings confirm that the overload provided by lower-limb WR is specific to the muscles used to produce the sprint running movement pattern. While not a replacement for general, nonspecific foundational training, lower-limb WR should be investigated as a movement- and speed-specific method of resistance training to improve sprint running speed.

At the beginning of this thesis, a total of five investigations had quantified the acute effects of lower-limb WR on sprint running performance measures. Four of these investigations loaded the whole leg by attaching external loads to the thigh and shank [6,55,95,97] while one other study utilised a load placement at the ankle [90]. The researchers primarily focused on measures of sprint times, speed, and step kinematics and provided general conclusions that lower limb WR ≤ 5% BM provides an overload appropriate for use during sprint running training. However, minimal kinetic and joint kinematic information had been published which limited the understanding of the underlying mechanics associated with sprint running with lower-limb WR. Also, no researchers had employed a shank- or thigh-only load configuration. To better determine how to use WR to target certain aspects of sprint running performance during training, more sophisticated analyses with additional loading schemes were needed. Further, there was no research-based evidence detailing how an athlete population might respond to lower-limb WRT for sprint running.

1.2 Thesis Rationale

The previous research in WR was limited and had yet to investigate the underlying acute mechanical changes that occur with lower-limb WR or the long-term effects of training with lower-limb WR in athletes. Determining the effects of training with lower-limb WR while engaged in a sport-specific movement task would be a first and was pre-requisite to uncovering how WR can be applied to sports training. That is, by understanding the movement adaptations that occur as an effect of lower-limb WRT, researchers and practitioners can better understand how the body responds to control the limb load and how this can be manipulated for performance improvements. Therefore, if deemed effective, WR can provide a highly individualised training tool to facilitate change in a valuable athletic ability. Initial evidence on the effects of lower-limb WR on sprint running performance confirmed that using lower-limb WR during sprint running allows the athlete to perform the sprint specific movement pattern in an overloaded manner with only minimal disruption to sprint running step kinematics [54]. Such findings provided a theoretical foundation for lower-limb WR as a resistance training method to improve sprint running performance. However, given the paucity of research regarding the utilisation of lower-limb WR for sprint running, further research was needed to better understand the effects of this type of training on the mechanical determinants of sprint performance.

1.3 Purpose of the Research

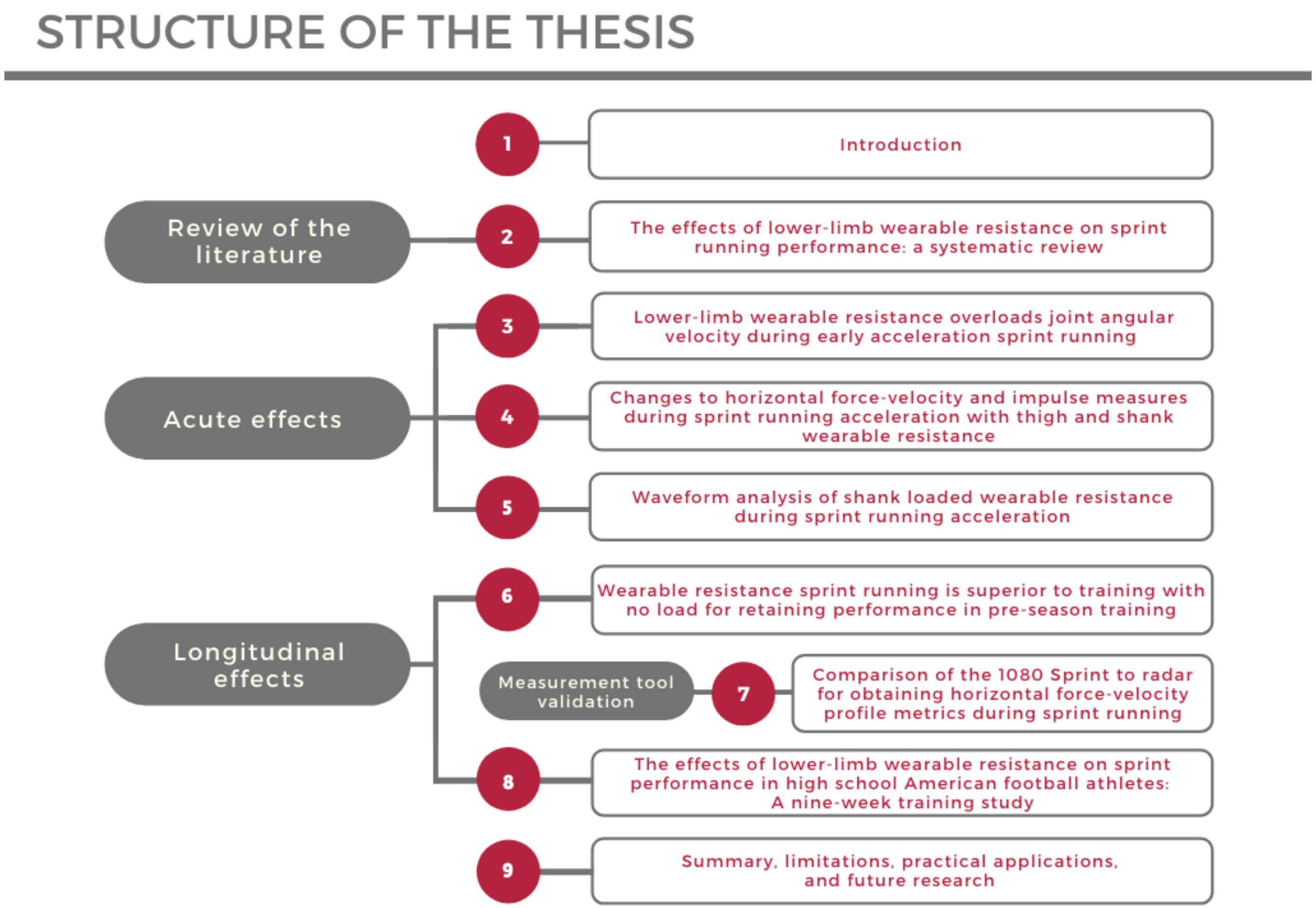
The purpose of this research was to answer the overarching question: "What are the effects of lower-limb WR on short distance sprint running?" This included investigating the underlying acute mechanical changes that occur with lower-limb WR and determining the effect of training with lower-limb WR on short distance sprint running. The findings provide practitioners with an assessment of the appropriateness of lower-limb WR as a training stimulus for sprint running performance and provide practical recommendations for programming WRT for sprint running. The specific aims of this research were to:

1. Review and evaluate the literature related to acute and longitudinal use of lower-limb WR during sprint running.
2. Assess the underlying acute mechanical changes that occur with lower-limb WR during sprint running as measured with high-speed motion capture and in-ground force measurement systems.
3. Establish the magnitude of systematic bias and random error of a motorised resistance training device for performing horizontal force-velocity profiling during sprint running.
4. Assess the effectiveness of training with lower-limb WR on short distance sprint running performance.
5. Provide practitioners with an evidence-based opinion of the appropriateness of lower-limb WR as a training stimulus for sprint running performance and provide practical recommendations for programming WRT for sprint running.

1.4 Structure of the Thesis

The chapters of this thesis were written in the format of a published journal article, except for the first and last chapters, per the thesis Pathway Two at AUT i.e. thesis by publication. The thesis is presented in nine chapters (see Figure 1), divided into three thematic sections. The first thematic section includes Chapter 2, a review of the literature investigating the acute and longitudinal effects of sprint running lower limb WR. The second thematic section comprises Chapters 3, 4, and 5, which investigated the acute underlying mechanical changes that occur with lower-limb WR during sprint running as determined with gold standard biomechanical equipment and measurement techniques. The third thematic section comprises Chapters 6 and 8, which examined the longitudinal effects of lower-limb WR use during sprint running. Included in the third thematic section is Chapter 7, which established the magnitude of systematic bias and random error of a motorised resistance training device for performing horizontal force-velocity profiling during sprint running which was used to inform equipment selection for Chapter 8. The last chapter, Chapter 9, is a summary of the research findings in context with previously reported literature and includes a discussion of the limitations of the research, practical applications of the research findings, and suggestions for future research directions.

Figure 1. Thesis structure



Chapter 2. The Effects of Lower-Limb Wearable Resistance on Sprint Running Performance: A Systematic Review

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Author contributions: Feser 85%, Macadam 10%, Cronin 5%

2.0 Prelude

According to the principle of training specificity, training should replicate the characteristics of the sporting action to enhance transfer of the training adaptation(s). A training method that enables a high degree of specificity for sprint running is lower-limb WRT. Though WR has increased in popularity, there was limited evidence supporting the choice of load placement and magnitude for training application. Further, the evidence was so limited that it was not feasible to perform a meta-analysis of the available studies. Therefore, the purpose of this chapter was to systematically review the literature that used lower-limb WR during sprint running to provide a summary and critique of the available scientific knowledge. From this treatise, the fundamental gaps and limitations were identified to guide the research direction of this thesis.

2.1 Introduction

Sprint running ability is a key performance factor in many sport activities such as track and field, rugby, and football. Several training options are available to produce speed adaptation, however, this adaptation needs to be specific to the sport and athlete requirements [2]. Though non-specific training plays a role in certain phases of a periodised plan, the transference of non-specific strength and power to speed and agility is usually minimal at best [26]. Based on the principle of training specificity, training options should replicate the characteristics of a sporting action so that training adaptations will optimally transfer to the sporting action [25]. One training method that enables such specificity for improving sprint performance is WR training. WR training involves attaching an external micro-load (i.e. loads as little as 0.5% BM) to different segments of the body. The load is worn during sport-specific movement training and is, therefore, a direct example of the application of the concept of training specificity (i.e. resisted movement training) [54]. Previous sprint WR studies have used loads attached to the upper-limbs [58,68,90], trunk [16,27,28], or lower-limbs [55,95]. These forms of resisted sprint training attempt to match the sprint training program design goals described by Cissik [14] of increasing neural activation and strength of the lower limbs, thus sprint velocity, without adversely affecting sprint technique.

The ability to load specific joints, and therefore specific muscles, by attaching external micro-loads to an athlete's limb(s) makes WR training, and in particular lower-limb WR, an attractive option for sprint training. However, attaching an external load directly onto the limb changes the limb's inertial properties. These changes are more prominent when the load is positioned in a more distal location on the limb and when load magnitude increases [66]. As the inertial properties of the limb are changed, there are accompanying biomechanical changes [66]. Practitioners interested in utilising lower-limb WR training to develop an athlete's sprint running capabilities must first understand the biomechanical changes that occur with limb loading while sprinting. Though WR sprint training has increased in popularity, there is currently limited evidence supporting the choice of load placement and magnitude for training application. The aim of this review was to evaluate the literature that has used lower-limb WR during sprint running to provide the practitioner with a summary and critique of the current scientific knowledge in this area.

2.3 Methods

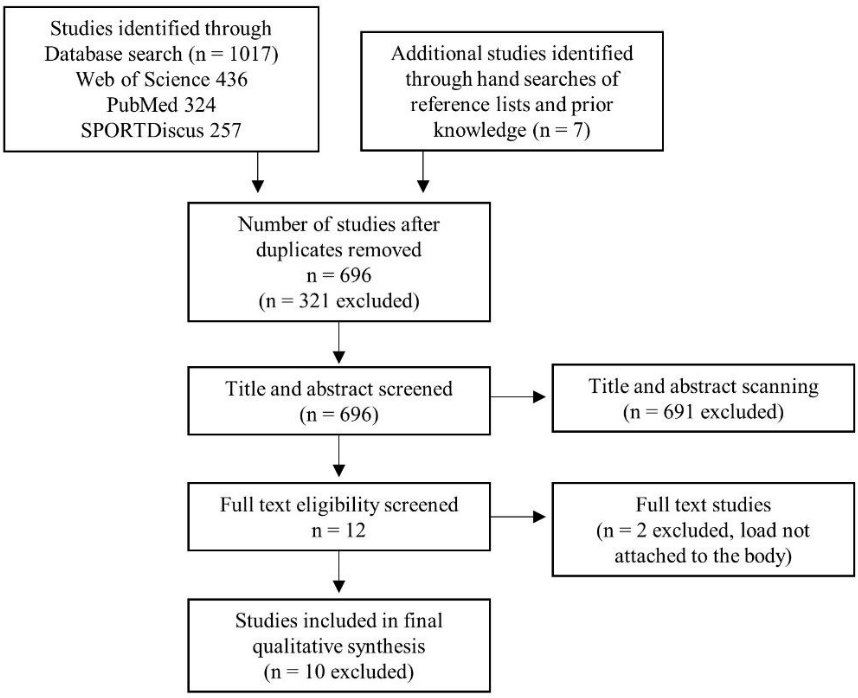
A systematic search, completed in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-analyses statement guidelines [70], was completed to identify research that had quantified the acute and longitudinal effects of lower limb WR on sprint running performance. The Boolean phrases (limb OR leg OR lower extremity) AND (sprint*) AND (resist* OR weight OR load*) were used for searches in PubMed, SPORTDiscus, and

Web of Science electronic databases from inception to November 2018. Following, any additional studies that met the inclusion criteria previously known by the authors or identified from the reference lists of the retrieved studies were also included.

Studies measuring the kinetic or kinematic effects of lower limb WR during sprint running that were published in peer-reviewed journals were included. The lower limb WR included loads attached to the thigh, shank, or foot, or any combination thereof. Additionally, studies that assessed sprint running immediately following WR use during sprint running (revealing acute performance effects) or following a WR training intervention were also included. Studies were excluded when the loads were not directly attached to the body, when sprint running was not performed at maximum effort (e.g. running speeds), and when results could not be extracted as numerical data (e.g. figures). Further, only the studies that included injury-free participants, regardless of age, gender, or training status were included. If the same study was published in multiple locations, one was retained while the others were considered a duplication and removed (e.g., Pajic, Kostovski, Ilic, Jakovljevic, and Preljevic [84] and Pajic [83]).

The outcome of search results from the electronic databases, reference list reviews, and prior knowledge resulted in 692 relevant studies (Figure 2). Following application of the inclusion and exclusion criteria, ten studies were included for review.

Figure 2. Flow of information through the different phases of the review



2.3 Results

Ten studies were analysed in this review, which consisted of 116 participants that completed a sprint running intervention with lower limb WR. A wide range of training status and sporting experience was included, ranging from healthy, untrained individuals to semi-professional and national level athletes. Cohen's *d* effect sizes (ES) were calculated for the variables reported as significant by the studies included in this review and were described as small (<0.5), moderate (0.51–0.79) and large (>0.8) [21]. The following sections report the acute kinematic and kinetic effects (Table 1), followed by the acute performance effects and longitudinal effects (Table 2).

2.3.1 Acute Effects on Sprint Running Kinematics

A total of eight investigations have assessed the acute effects of lower limb WR on movement kinematics when sprint running (see Table 1). Four investigations loaded the whole leg by attaching WR to the thigh and shank [6,55,95,97]. two investigations utilised a thigh loading scheme and a separate shank loading scheme [34,49], while one other study utilised a load placement at the ankle [90]. The following sections will summarise the kinematic effects of lower limb WR on sprint time and velocity, the start, acceleration, and maximal velocity phases of sprint running, and compare differences in WR location and magnitude.

Sprint Times and Velocity

Five of the studies included in this review reported sprint times. The WR used in these studies consisted of 10% of individual segment mass [6], 3% BM [55,97], and 5% BM [97] placed on the thigh and shank, 2% BM placed on the thigh [34], and 2% BM placed on the shank [34]. The only statistically significant difference in total sprint times from the unloaded condition was found when loads of 5% BM were utilised. Specifically, Simperingham and Cronin [95] reported the average 25 m non-motorised treadmill sprint time was increased 3.3% (ES = 0.43) with 5% BM WR. Simperingham et al. [97] reported the average 20 m over ground sprint time to be increased 2.0% (ES = 0.37) with 5% BM WR. The latter was also a significant increase from the 3% BM condition used in Simperingham et al. [97]. Use of 3% BM in the Simperingham et al. [97] study did not result in a significant difference in total sprint time from the unloaded condition which was consistent with other studies that utilised WR of 3% BM [55] or less [6,34]. Two studies also estimated the theoretical maximal velocity, which was reported to be significantly changed from the unloaded conditions in Simperingham et al. [97] by –3.6% (ES = 0.50) with 3% BM WR and –6.0% (ES = 0.83) with 5% BM WR and in Macadam et al. [55] by –6.5% (ES = 0.84) with 3% BM posterior load location WR and –5.4% (ES = 0.60) with 3% BM anterior load location WR.

Start Phase Kinematics

When assessing the effect of lower limb WR on the start phase (as defined as the first two steps), contact time has shown to be significantly increased by 3.4–5.0% (ES = 0.41–0.49) with 3% BM WR [55,97] and by 5.0% (ES = 0.48) with 5% BM WR [97] while any changes to flight time, step frequency, and step length were non-significant. Macadam et al. [55] also reported vertical stiffness to be significantly reduced by –6.4% (ES = 0.38) and –8.3% (ES = 0.50) with anterior and posterior 3% BM WR, respectively.

Acceleration Phase Kinematics

Lower limb WR appears to have a slightly greater effect on the acceleration phase (defined as steps 3–8) [55,97] or steps 3–12 [95] compared to the start phase of sprint running as researchers have reported a significant decrease in step frequency in addition to significant increases to contact times when the WR magnitude is equal to 3% BM or greater [55,95,97]. An exception to this was Feser et al. [34] who found 2% BM WR placed on the shank to significantly decrease step frequency (–2.1%, ES = 0.34) with no corresponding significant increase to contact time. Contact time was reported to be increased by 3.0% (ES = 0.39–0.41) with 3% BM WR [55] and by 4.3% (ES = 0.66) and 6.0% (ES = 0.71) with 5% BM WR compared to the unloaded conditions [95,97]. Step frequency was reported to significantly decrease with both 3% and 5% BM WR by –2.0 to –3.6% (ES = 0.31–0.44) and –3.0 to –3.7% (ES = 0.52–0.63), respectively, as compared to the unloaded condition [55,95,97]. While step length changes remained non-significant through the acceleration phase, the significant step frequency changes resulted in significant split time differences with 3% and 5% BM WR. These split time increases appeared significantly different from the unloaded condition at the 15 m [95], 20 m mark [97], and from 10–20 m [55].

Simperingham and Cronin [95] also reported peak velocity during the acceleration phase which was found to be significantly reduced by –2.3% (ES = 0.44) with 5% BM WR. Vertical stiffness measures were reported to be significantly lower, by –6.2% (ES = 0.38), when the 3% BM WR was positioned on the posterior leg (thigh and shank) but the corresponding decrease in stiffness when the 3% BM WR was positioned on the anterior surface of the leg was non-significant (–5.8%) [55]. It is important to note that no other variables were found to be significantly different from the unloaded condition due to the anterior versus posterior loading nor was there any statistical differences found between the anterior and posterior load positions [55].

Maximal Velocity Phase Kinematics

Researchers from six different studies have reported kinematic results for the maximal velocity phase of sprint running. Velocity was found to be significantly decreased (or decreased by a clear possible difference) by –1.3% to –12.8% in all studies [6,34,49,90,95,106]. All but one research group found step frequency and contact times to be significantly reduced or reduced by a clear possible difference/likely clear difference by –1.4% to –3.5% and 1.7% to 4.7%, respectively, with WR placed on the shank [34,49], thigh [34,49], or across the whole leg [95]. Flight time was also found to be changed ($p < 0.05$) with shank WR by 3.3% (ES = 0.42) with 2% BM WR [34] and possible clear difference of 2.7% with 0.6% BM WR [49].

Table 1. Effects of limb loading on sprint performance and biomechanical variables reported as percent change from the baseline unloaded condition (*n* = 8)

Author	Participants (sex and mean ± SD age, height, and mass) Training Status	Sprint Distance	WR Loading	Sprint Performance (distance, % change, ES)	Kinematic Results (variable, % change, ES)	Kinetic Results (variable, % change, ES)
Ropret et al., 1998	24 males, 20.1 ± 0.9 years, 179.6 ± 8.4 cm, 74.5 ± 9.8 kg PE students, 18 active in a variety of sports activities	30 m sprint, overground	1.6% BM, 3.2% BM, 4.8% BM; Ankle		AP (4.8% BM): velocity −7.8%** (NA) MVP (4.8% BM): velocity −12.8%** (NA)	
Bennett et al., 2009	8 males, 26.0 ± 7.3 years, 177.3 ± 3.4 cm, 77.3 ± 3.9 kg National level competitive beach sprinters (athletes' 100m PR was 88% of current world record)	40 m sprint, overground	2.4% BM; Whole leg, at radius of gyration	0-10 m −0.6% 10-20 m 4.2%** (1.6) 20-30 m 3.7% 30-40 m 7.4%** (2.2) 40 m 3.1%	MVP: Stride velocity −4.7%** (1.8) CT 8.9% FT 0.8% SF −2.2%	
Simperingham & Cronin, 2014	8 males, 29.2 ± 3.8 years, 177.1 ± 7.5 cm, 81.8 ± 9.7 kg Athletic at least 2 years of experience playing sprint-based team sports	6 s sprint, non-motorised treadmill	5% BM; Whole leg	2 m −1.8% 5 m 0.0% 10 m 1.1% 15 m 2.1%* (0.26) 20 m 2.5%* (0.32) 25 m 3.3%* (0.43) 10-20 m 5.2%* (0.66)	AP: Peak velocity −2.3%* (0.44) CT 4.3%* (0.66) FT 0.0% SPF −3.7%* (0.63) SL 6.0% MVP: Peak velocity −5.3%* (0.66) CT 4.7%* (0.60) FT 4.7% SPF −3.5%* (0.66) SL −1.7%	AP: F_v 4.0%* (0.22) $F_v$mean 4.1%* (0.23) F_h 0.6% Pmax −0.8% $F_v$rel −0.9% $F_v$mean.rel −0.8% MVP: F_v 4.5%* (0.28) $F_v$mean 4.1% F_h 1.9% Pmax −3.1% $F_v$rel −0.8% $F_v$mean.rel −1.5%
Simperingham et al., 2016	15 male, 19.0 ± 0.5 years 181.2 ± 7.3 cm, 91.0 ± 17.4 kg Rugby union athletes	20 m sprint, overground	3% BM; Whole leg	5 m −1.5% 10 m −0.5% 20 m 0.6% V_0 −3.6%* (0.50)	SP: CT 5.0%* (0.41) FT −19.4% SPF −1.5% SL 0.8% AP: CT 5.0%* (0.55) FT −3.8% SPF −2.0%* (0.31) SL 0.0%	F_{0rel} 6.25% $Pmax_{rel}$ 1.2% S_{Fvrel} 10.0%* (0.72)

			5% BM; Whole leg	5 m 10 m 20 m V_0	0.7% 0.9% 2.0%* (0.37) −6.0%* (0.83)	SP: CT FT SPF SL AP: CT FT SPF SL	 5.0%* (0.48) −17.7% −2.0% 0.0% 6.0%* (0.71) −3.8% −3.0%* (0.52) −0.6%	F_{0rel} $Pmax_{rel}$ S_{Fvrel}	1.3% −4.2% 6.1%
Macadam et al., 2017	19 male, 19.7 ± 2.3 years, 181 ± 6.5 cm, 96.1 ± 16.5 kg Amateur to semi-pro rugby, 2+ years sprint training and currently engaged in periodised S&C program	20 m sprint, overground	3% BM; Whole leg, anterior	2 m 5 m 10 m 20 m 10-20 m V_0	−1.2% 0.0% 0.0% 0.8% 2.2%* (0.35) −5.4%* (0.60)	SP: CT FT SPF SL VS AP: CT FT SPF SL VS	 3.4%* (0.41) −7.3% −1.3% 0.0% −6.4%* (0.38) 3.0%* (0.39) 1.3% −3.4%* (0.42) 0.0% −5.8%	F_0 Pmax S_{Fv} F_{0rel} $Pmax_{rel}$ S_{Fvrel}	5.4% 1.5% 12.2%* (0.46) 5.5% 0.0% 9.9%* (0.62)
			3% BM; Whole leg, posterior	2 m 5 m 10 m 20 m 10-20 m V_0	−1.2% 0.0% 0.5% 1.4% 2.9%* (0.50) −6.5%* (0.84)	SP: CT FT SPF SL VS AP: CT FT SPF SL VS	 4.4%* (0.49) −7.3% −1.3% 0.8% −8.3%* (0.50) 3.0%* (0.41) 2.5% −3.6%* (0.44) 0.0% −6.2%* (0.38)	F_0 Pmax S_{Fv} F_{0rel} $Pmax_{rel}$ S_{Fvrel}	4.7% 0.6% 11.7%* (0.51) 5.1% −1.3% 9.9%* (0.62)
Feser et al., 2018	11 male, 21.2 ± 2.6 years, 175.3 ± 5.5 cm, 68.7 ± 4.3 kg Track and Field amateur athletes with 9.7 ± 2.9 years of sprint-based training	50 m sprint, overground	2% BM; Shank, mid	10 m 50 m	−0.5% −0.2%	Peak velocity AP: CT FT SPF	−1.8%* (0.37) 2.0% 2.0% −2.1%* (0.34)		

			2% BM; Thigh, distal	10 m 0.5% 50 m 0.3%	SL 0.0% SW 0.0% <u>MVP:</u> CT 2.9%* (0.42) FT 3.3%* (0.42) SPF –2.5%* (0.52) SL –0.5% SW 0.0% Peak velocity –2.0%* (0.40) <u>AP:</u> CT 2.6% FT 0.0% SPF –1.4% SL 0.0% SW 0.0% <u>MVP:</u> CT 3.8%** (0.57) FT 0.0% SPF –1.4%* (0.31) SL –0.5% SW 11.1%	
Hurst et al., 2018	6 male and 2 female, 21 ± 1 years, 172 ± 9 cm, 70.4 ± 6.4 kg University level sprinters	40 m sprint, overground	0.6% BM; Shank, anterior at +4.5% moment of inertia 1.7% BM; Thigh, anterior at +4.5% moment of inertia		<u>MVP:</u> Step velocity –1.3%†† (0.18) CT 1.7%†† (0.17) FT 2.7%†† (0.26) SPF –2.2%††† (0.34) SL 1.0%† <u>MVP:</u> Step velocity –1.8%†† (0.23) CT 2.6%††† (0.26) FT 4.6% SPF –3.8%††† (0.56) SL 1.5%	
Zhang et al., 2018	16 males, 21 ± 2 years, 176 ± 4 cm, 67.41 ± 5.72 kg Sub-elite sprinters	40 m sprint, overground	1.1% BM; Shank, 39.3% of shank length away from knee joint centre		<u>MVP</u> Velocity –2.2* (0.40) Landing distance 5.3% Landing height 0.0%	

					Take-off distance –3.7%	
					Take-off height 0.0%	
					Hip joint LA 1.9%	
					Knee joint LA –5.1%* (0.28)	
					Ankle joint LA 5.5%	
					Hip joint TA 16.5%	
					Knee joint TA –1.8%	
					Ankle joint TA –12.7%	

Note: SD = standard deviation; ES = effect size; BM = body mass; NA = not enough information provided to calculate effect size; CT = contact time; SF = stride frequency; SPF = step frequency; SL = step length; VS = vertical stiffness; SP = start phase; AP = acceleration phase; MVP = maximal velocity phase; F_v = vertical ground reaction force; F_h = horizontal ground reaction force; Pmax = maximal horizontal power; rel = relative to system mass; V_0 = theoretical maximal velocity; F_0 = theoretical maximal horizontal force; S_{Fv} = slope of the force-velocity curve; WR = wearable resistance; * = $p < 0.05$; ** = $p < 0.01$; † = possible trivial difference; †† = possible clear difference; ††† = likely clear difference; LA = angle at landing; TA = angle at take-off

Additionally, researchers from two studies measured changes in joint kinematics with lower limb WR. Bennett et al. [6] reported no differences ($p < 0.05$) between the 2.4% BM whole leg WR condition and the unloaded condition for sagittal plane hip and knee joint angular displacement or velocity variables. Zhang et al. [106] found no significant changes to take-off and landing hip, knee, and ankle angles, distance, or height. However, knee joint landing angle was significantly decreased by 5.1% (ES = 0.28) (more knee extension) with shank WR. Furthermore, Zhang et al. [106] found that although the WR used in their study significantly reduced sprint running velocity, it did not significantly change the relationship of sprint running velocity with the measured kinematic variables at landing and take-off.

2.3.2 Acute Effects on Sprint Running Kinetics

Three studies have reported the kinetic effects of lower-limb WR [55,95,97]. Each of these studies utilised a 3% or 5% BM whole limb (thigh and shank) WR scheme. Those that investigated the effect of 3% BM WR on sprint kinetics found significant changes to the relative force-velocity (F-v) profile of 10.0–11.0% reflecting a more force dominant F-v profile (ES = 0.62–0.72) [55,97]. Furthermore, Simperingham et al. [97] found a significant increase of 9.0% in F_0 when expressed relative to body mass. When comparing kinetic outputs during the start, acceleration, and maximal velocity phase, Simperingham and Cronin [95] reported no differences ($p < 0.05$) for mean vertical ground reaction force values between the unloaded and WR conditions during the start and maximal velocity phase while there was a significant increase during the acceleration phase.

2.3.3 Differences Between WR Locations and Magnitudes

Regarding lower limb WR sprint running kinematics, two studies have assessed the effects of differences between WR locations and one study assessed the effects of differences between WR magnitudes. Concerning differences in placement, Macadam et al. [55] found no statistically significant differences when 3% BM WR was placed on the anterior versus the posterior of the leg for any of the variables measured. Feser et al. [34] reported a significant difference for flight time when 2% BM WR was placed on the shank versus the thigh. Specifically, the shank WR produced a 3.3% (ES = 0.47) increase in flight time over the thigh WR condition.

When the magnitude of WR was increased from 3% to 5% BM, a significant difference in 20 m sprint times and maximal horizontal power output was found. The 5% BM WR condition produced slower (–1.4%) sprint times and lower (–5.8%) relative maximal horizontal power output values than the 3% BM condition [97]. Neither of these WR conditions produced a significant difference from the unloaded condition; the 3% BM WR produced a slight increase (1.2%) and the 5% BM WR produced a decrease (–4.2%) in relative maximal horizontal power output. Furthermore, a significant change (10.0%, ES = 0.72) in the slope of the F-v curve was found with 3% BM WR but not with 5% BM WR (–6.1%). Therefore, both WR loads resulted in a more force-oriented F-v curve but only 3% BM WR produced a significant change from the unloaded condition.

2.3.4 Acute Performance and Longitudinal Effects

The effects following lower-limb WR use on sprint running performance have only been minimally investigated. Three studies measured the changes that occur to sprint running performance immediately following a single session lower-limb WR intervention (referred to as acute performance effects) [6,95,96]. One study measured the changes that occur to sprint running performance following a six week long lower-limb WR intervention [84].

Researchers that measured the changes to sprint running performance following the use of lower limb WR reported no significant change to total sprint times measured up to 40 m [6,96]. Simperingham et al. [96] found during a single-subject study design that start and acceleration phase kinematics to be substantially changed (greater than two standard deviations from baseline) following a series of 40 m sprints completed with 1%, 3%, and then 5% BM whole leg WR. More specifically, contact time was substantially increased by 2.9% (start phase) and 2.1% (acceleration phase) with a substantial decrease in 10 m sprint time by −3.3%. During the maximal velocity phase, Simperingham et al. [96] found substantial changes to both flight time (3.2%) and step frequency (–2.5%) with only a slight increase to the 30–40 m split time (1.8%). Bennett et al. [6] reported no significant changes to 40 m sprint times following a 2.4% BM whole leg WR protocol while Simperingham and Cronin [95] reported that a 5% BM WR protocol did not result in significant changes to running performance aside from a 1.3% increase in vertical ground reaction force production.

A six-week training study utilising 5% BM ankle WR was found to elicit a significant increase in stride length (5.3%, ES = 0.43) and decrease in stride frequency (–5.6%, ES = 0.54) as measured between 25–50 m with no significant changes to maximal running speed [84]. Furthermore, this training was found to have significantly increased all angles measured (knee angle at take-off, knee angle at contact, knee flexion during backswing, and elbow flexion during backswing) suggesting a more upright body posture. The control group did not experience any statistically significant kinematic changes following the training.

Table 2. Acute performance and longitudinal effects of limb loading on sprint performance and biomechanical variables (n = 4)

	WR Loading	Participants (sex and mean ± SD age, height, and mass)	Training Protocol	Sprint Performance (distance, % change)		Results (variable, % change)	
Acute performance effects							
Bennett et al., 2009	Whole leg; 2.4% BM	8 males, 26.0 ± 7.3 years, 177.3 ± 3.4 cm, 77.3 ± 3.9 kg National level competitive beach sprinters	7 repetitions of 40 m sprints; 2 unloaded (pre-test), 2 loaded, 3 unloaded (post-test).	0–10 m 10–20 m 20–30 m 30–40 m 40 m	0.0% 2.6% −1.8% 1.8% 0.3%	MVP: stride velocity CT FT SF	 −0.8% 2.2% −0.8% 0.4%
Simperingham & Cronin, 2014	Whole leg; 5% BM	8 males, 29.2 ± 3.8 years, 177.1 ± 7.5 cm, 81.8 ± 9.7 kg Athletic with at least 2 years of experience playing sprint-based team sports	4 sets of 2 max effort 6 s sprints, non-motorised treadmill; Sets 1 and 4 unloaded, sets 2 and 3 torso or leg loading randomised			MVP F_v	 1.3%* (NA)
Simperingham et al., 2015	Whole leg; 1%, 3%, 5% BM	1 male, 29.2 years, 180.8 cm, 87.2 kg Rugby union athletes	3 x 40 m loaded accelerations with 1%, 3%, 5% BM	10 m 30 m 40 m 30–40 m	−3.3%† −0.7% 0.0% 1.8%	SP: CT FT SPF SL VS AP: CT FT SPF SL VS MVP: CT FT SPF SL VS	 2.9%^ −1.8% −1.4% 1.8% −5.0% 2.1%^ 1.2% −1.8%^ 1.3% −6.1% 1.9% 3.2%^ −2.5%^ 0.5% −1.5%
Longitudinal effects							

Pajic et al., 2011	Ankle; 5% BM	6 individuals, gender not specified 20.4 ± 1.7 years, 178.4 ± 8.12 cm, 71.4 ± 8.5 kg Untrained	6-week duration; 5 repetitions of 50m sprints; increased to 2 sets for weeks 3 and 4, increased to 3 sets for weeks 5 and 6		<u>MVP:</u> velocity SF SL	 −0.5% −5.6%** (0.54) 5.3%** (0.43)

Note: SD = standard deviation; ES = effect size; BM = body mass; NA = not enough information provided to calculate effect size; CT = contact time; SF = stride frequency; SPF = step frequency; SL = step length; VS = vertical stiffness; SP = start phase; AP = acceleration phase; MVP = maximal velocity phase; WR = wearable resistance; * = $p < 0.05$; ** = $p < 0.01$; † = more than 2 standard deviations from baseline mean.

2.4 Discussion

A specific concern with resisted sprint training is that the added load can unfavourably change sprint kinematic variables such as stride or step length, ground contact times, and stride or step frequency during the training. The micro-loading induced by the WR studies completed to-date (0.6%–5% BM) appeared to consistently affect some of the commonly measured kinematic variables (in particular step frequency and contact time) when the load was partitioned across the whole leg, thigh, or shank. When the load was solely located on the end of the lower-limb (at the ankle), thus inducing a greater increase in limb inertia, an estimated 4.8% BM load resulted in a significant decrease in sprint velocity though stride length was unaffected. Practitioners may be interested in utilising higher loads, to the extent deemed comfortable by the athlete, to induce a greater loading stimulus, especially if looking to overload the start phase specifically. While step kinematic changes appeared to be cumulative from the start to the maximal velocity phase, participants appear to be able to maintain stride length which may further suggest joint kinematics are minimally affected when sprint running with an added 5% BM load on the lower-limbs. This may alleviate practitioner concerns that training with lower-limb WR negatively affects movement technique.

Many different lower-limb WR configurations and magnitudes can be used during sprint running. Researchers thus far have investigated the effects of whole limb, thigh, shank, or ankle WR on sprint performance. When comparing the different WR location options, it appears the effects on sprint running performance were consistent. Specifically, all reports found that running velocity was affected as a result of the concomitant change in stride rate but not stride length [6,34,49,55,95,97], with the exception of a possible trivial difference found by Hurst et al. [49] for step length with shank WR. This, along with the lack of significant changes to joint kinematics found in Bennett et al. [6] and minimal changes to joint kinematics found in Zhang et al. [106] (all effect sizes under 0.28) reiterates the possibility that lower limb WR up to 5% BM could be used without significant coinciding changes to joint movements. Though further research is needed into this area.

Practitioners interested in WR should also understand the kinetic responses to limb loading to best determine how the loading stimulus can be utilised as a sprint running training tool. WR of 3% BM was found to elicit moderate changes (10.0–11.0%, ES = 0.62–0.72) to the relative F-v profile, reflecting a more force dominant profile [55,97]. Furthermore, these researchers noted that F_0 was increased by ~5.0%–9.0% [55,97]. Although F_0 has not been shown to be significantly correlated to sprint performance (i.e., max speed, mean 100 m speed [72]) it has been reported that sprinting expertise through the acceleration phase is characterized by an ability to produce higher amounts of horizontal net force at each step [71,72,86]. Together these findings indicate that a 3% BM lower-limb WR may provide a stimulus to increase horizontal force output during 20 m sprints and, therefore, it may be concluded that lower-limb WR has the potential to elicit improved sprinting performance over time through greater horizontal force production.

It is important to note that sprinting expertise through the acceleration phase is marked by an ability of the athletes to apply more horizontally oriented (not greater) forces [71,72,86]. It is unclear if the participants included in the studies reviewed here responded to the loading by producing greater horizontal forces or merely reoriented the resultant force vector more horizontally as ground reaction force values were not directly measured in these studies, nor are enough details presented to make a conclusion. However, there remains the possibility that practitioners may be able to utilise lower-limb WR to encourage more horizontally directed force production during the acceleration phase (via increased total force production or a reorientation of the force vector). It can also be concluded that the 3% BM WR successfully provided an overload stimulus for sprint running as theoretical maximal velocity values were significantly reduced with WR [55,97]. This is an important factor considering one of the mechanical determinants of high levels of acceleration and 100 m sprint performance is a velocity oriented F-v profile [72]. Considering the relationship of maximal horizontal force production and maximal running velocity to an individual's maximal mechanical power capabilities, a training program intended to improve sprint acceleration performance should focus on improving both components of maximal horizontal power production [73].

Previously researchers have suggested the value of high vertical force production to achieving fast speeds during maximal velocity running [71,72,104]. From our results, it seems that a 5% BM lower limb WR may not overload the system enough to provoke greater vertical force production values during maximal velocity running as Simperingham and Cronin [95] reported no significant differences for mean vertical ground reaction force values between the unloaded and WR conditions during the maximal velocity phase. However, this is in contrast to the significant increase in mean vertical ground reaction force values that were produced during the acceleration phase, further indicating that the effect of a given WR load varies for each phase of sprint running.

Minimal information has been reported on the acute performance effects of lower-limb WR use for sprint running. From the literature reviewed it would seem that the removal of WR can produce immediate changes to sprint running kinematics with negligible effects to total sprinting time. How long these effects last is unknown. Due to limited research into acute performance effects with lower-limb WR use, further research is required to assess how protocols affect the different phases of sprint running to find an optimum loading scheme and distance protocol.

Only one longitudinal study has investigated the effects of lower-limb WR training on sprint performance. It was observed that 5% BM ankle WR elicited a significant increase in stride length (5.3%, ES = 0.43) and decrease in stride frequency (–5.6%, ES = 0.54) with no changes (ES = 0.12) to maximal running speed [84]. While increases in running speed over time have been shown to coincide with an increase in step length and is believed to be important for the development of maximal speed sprinting [79], the accompanying decrease in stride frequency seen in [84] is counterproductive to the development of maximal speed sprinting. Ultimately, it is difficult to apply these study findings as untrained participants were used and there is no information regarding the start and acceleration phases of sprinting. Additionally, with only one post-test time period completed any effects of off-loading the WR are unknown.

Given the paucity of research regarding the utilisation of lower-limb WR for sprint running, further research is needed to better understand the effects of this type of training on the mechanical determinants of sprint performance and how WR can be best integrated into a sprint training regime. The studies that have been published to-date on the effects of lower-limb WR on sprint running kinematics have only provided minimal information on changes to body posture and lower-limb angular kinematics with no information presented during the start or acceleration phases of the sprint. Recently researchers have shown that lower-limb angular kinematic changes are associated with improved sprint performance [10] and it has long been accepted that technical ability is of high importance to sprint running performance over simply being able to dynamically produce large forces [71]. Therefore, it is of value to further investigate if lower-limb WR can be used to induce positive changes to joint angular kinematics and total body posture in relation to sprint performance through the start, acceleration, and maximal velocity phases.

Additional evidence on the acute effects of lower-limb WR on sprint running kinetics would be valuable to further understand how the WR load may be used to target certain aspects of sprint performance for training. Limited information has been published regarding force production values. The addition of information related to the index of force application and ratio of horizontal force to total force (as seen in Rabita et al. [86]) would be necessary to determine if athletes simply reorient force vectors with WR or if the WR stimulates an increase in total force production. Finally, more studies are needed to understand the utility of lower-limb WR as a longitudinal training intervention for sprint performance. Once the effects of this type of training on sprint performance is determined, further training interventions could consider targeting particular phases of sprint running (i.e., start, acceleration, maximal velocity) as it is possible that different load magnitudes and/or orientation may need to be used to provide a desired overload within each phase.

Lower-limb WR is a form of resisted sprint training that allows for the athlete to perform the sprint specific movement patterns in an overloaded manner with no changes to step or stride length. WR may be used to target certain aspects of sprint running. Practitioners may choose to utilise lower limb WR for an athlete needing to selectively overload stride frequency or encourage more horizontally directed force production during short-distance sprint running or for the acceleration phase of longer distance sprint running. To target increased force production through the maximal velocity phase of sprinting, it is likely loading greater than 5% BM are needed to overload the system in the vertical direction. Lastly, considering the increased rotational inertia from WR, practitioners must take care to progressively overloading the athlete, especially during the beginning of the training season, to reduce possible risk of injury.

Chapter 3. Lower-Limb Wearable Resistance Overloads Joint Angular Velocity During Early Acceleration Sprint Running

This chapter comprises the following manuscript, which is under review at the European Journal of Sport Science.

Feser EH, Neville J, Wells D, Diewald S, Bezodis NE, Clark K, Nagahara R, Kameda M, Macadam P, Uthoff A, Tinwala F, Cronin JB. Lower-limb wearable resistance overloads joint angular velocity during early acceleration sprint running. *Eur J Sport Sci.* (under review).

Author contributions: Feser 80%, Neville 4%, Wells 3%, Diewald 2%, Bezodis 2%, Clark 2%, Nagahara 1%, Kameda 1%, Macadam 1%, Uthoff 1%, Tinwala 1%, and Cronin 2%

3.0 Prelude

A main finding in Chapter 2 was that the effect of wearable resistance on joint kinematics during the acceleration phase of sprint running had yet to be investigated. Additionally, researchers had yet to investigate the effects of using the same load magnitude (e.g. 2% BM) on two different limb segments (i.e. thigh versus shank). A specific concern with WR loading and training is that the added load could negatively affect joint kinematics, so further investigation of the acceleration phase of sprint running was warranted. Therefore, the purpose of this chapter was to conduct a three-dimensional motion-capture analysis to examine the effects of two different WR placements (i.e. thigh and shank) on joint kinematics during sprint running acceleration. The chapter helps practitioners understand how changing the limb's inertial properties with WR influences joint kinematics and how to incorporate this information when programming training with lower-limb WR.

3.1 Introduction

WR loading involves attaching an external load to one or more of the segments of the body. The low load magnitude used with this training method (e.g. ≤ 5% of BM [36]) allows for targeted resistance-based training during sports-specific movement tasks. Practitioners can selectively place a WR load to overload specific joints, and therefore, target specific muscles and specific muscular adaptations. This has made thigh- or shank-placed WR an attractive training option for sprint running. However, an external load attached to a limb changes the limb's inertial properties and can potentially alter joint kinematics during movement training. This is an important consideration for using lower-limb WR for sprint running.

The influence of thigh or shank WR on leg joint kinematics during sprint running has primarily been investigated during maximal velocity overground sprint running. Researchers have reported mean changes to joint position and limb segment displacement measures to be within ± 3° with thigh (~1.7% BM) [48] and shank (~0.6–1.1% BM) [48,107] WR. These reported measures were non-significant [48,107], with the exception of knee joint angle at touchdown, where sprint running with 1.1% BM shank WR resulted in a small, significant decrease in knee flexion (–1.7°, ES = 0.28, $p = 0.03$) [107]. The loading schemes evaluated to-date do not appear to produce aberrant movement patterns during maximal velocity sprint running. However, the characteristics of typical joint kinematics during unloaded sprint running change as an athlete transitions through acceleration to maximal velocity [77]. Therefore, the effects of thigh and shank WR on joint kinematics during acceleration should also be investigated.

The available research on the acute effects of lower-limb WR on acceleration phase joint kinematics is limited to one study published to-date. Researchers investigated the effect of sprint running with 2% BM thigh WR compared to unloaded sprint running on thigh kinematics and found non-significant increases in thigh flexion and extension displacement ranging from 0.8° to 2.8° across the acceleration phase (ES = 0.10–0.27, all $p > 0.05$) [59,62]. It seems that thigh angular displacement is minimally affected by the increase in rotational inertia from 2% BM thigh WR. Although thigh angular velocity was significantly decreased during all step phases measured (–2.3 to –8.0%, ES = 0.26–0.51, $p < 0.05$; steps 1-2, 3-6, and 7-10), the rotational work at the hip joint was significantly increased with the thigh WR (9.8–18.8%, ES 0.09–0.55, $p < 0.01$) [59]. However, the joint kinematic measures at the knee and ankle joints were not reported, nor, is there currently any information available on the effects of shank WR on acceleration phase joint kinematics during overground sprint running. Comparing the effect of thigh versus shank WR is especially important considering the progressive increase to the moment of inertia about the hip joint as a given WR load is placed more distally during sprint running [31].

Researchers have begun to establish how lower-limb WR may influence joint kinematics during sprint running but further investigation is needed to better understand the effect of thigh and shank WR on hip, knee, and ankle joint kinematics during sprint running acceleration. The information available to date is limited for the acceleration phase since only one WR load placement (thigh) has been used and one joint (hip) has been analysed. The outcomes of this study will help improve practitioner understanding of how changing the limb's inertial properties with shank or thigh WR influences joint kinematics across the whole leg, enabling them to make more informed decisions when programming training with lower-limb WR. Therefore, the primary purpose of this study was to determine the effect of two different WR placements (thigh and shank) on hip, knee, and ankle joint kinematics during the acceleration phase of sprint running. It was hypothesised that any significant changes to the joint position when loaded would be of a small effect and any significant changes to angular velocity would be classified as small or moderate.

3.2 Methods

3.2.1 Participants

Eighteen male, university-level sprint specialists volunteered to participate in this study (age = 20.9 ± 2.05 years, mass = 66.3 ± 5.06 kg, height = 1.74 ± 0.05 m). The athletes had a combined training experience of 9.17 ± 2.57 years and a mean 100 m best time of 11.46 ± 0.40 s. All study procedures were approved by the host University Institutional Review Board. Each athlete provided written informed consent prior to study participation.

3.2.2 Experimental Procedures

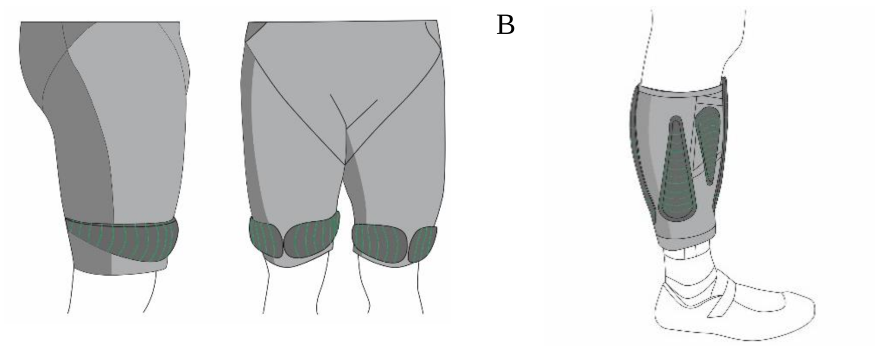
Athletes reported to the testing facility for two randomly ordered testing sessions, separated by a minimum of 72 hours. One testing session utilised thigh WR for the loaded experimental condition while the other utilised shank WR. Each testing session began with the athletes completing a self-selected warm-up and then four maximal effort 50 m sprints from the starting blocks. Each sprint trial was separated by a minimum of five minutes rest. Two sprints were completed under each experimental condition – loaded (with thigh or shank WR) and unloaded (no WR). The order of the sprints and the loading conditions were randomly assigned. When the athletes returned on the second day of testing, the experimental procedures were repeated except the alternate WR placement was utilised for the loaded trials.

Each sprint trial was completed on an indoor track surface (Hasegawa Sports Facilities Co., Hasegawa, Japan). An electronic starting gun (Digi Pistol, Molten, Hiroshima, Japan) was used to signal the start of each sprint. A retro-reflective marker set to record three-dimensional kinematics of the lower limb and torso was affixed to the athletes. The position of the wearable resistance limited the placement of markers on the loaded segment, so two marker sets were developed, one for each condition (Appendix I). The relevant marker set applied was a modified version of the University of Western Australia (UWA) lower limb marker set [7]. At the start of each testing session, the athletes performed a static pose calibration trial to determine anatomical landmark positions of the knee and ankle. The marker data were recorded at 250 Hz by a high-speed motion capture system (Motion Analysis Corporation, Santa Rosa, California, USA, 21 Raptor-E cameras) to capture the first 9 m of the acceleration phase of the sprint. The 10 m sprint times were measured using a photocell system (TC Timing System; Brower Timing Systems, Draper, UT, USA), initiated by the electric starting gun.

The WR was attached to the limb with a specialised form-fitting garment (Lila™ Exogen™, Sportboleh Sdh Bhd, Kuala Lumpur, Malaysia) that allows for Velcro backed micro-loads to be attached to the garment. The Exogen™ garments were worn for all sprint trials. For the thigh-loaded experimental condition, WR was attached to the Exogen™ shorts in a horizontal orientation on the distal aspect of the thigh. Consistent with previous thigh WR research, 2/3 of the load was placed more anteriorly and 1/3 placed more posteriorly (Figure 3A) [59,61]. For the shank-loaded experimental condition, WR was attached to the Exogen™ calf sleeves along the long axis of the shank in a manner to balance the loading around the limb (Figure 3B). The exact loading magnitudes ranged from 1.92–2.06% of BM due to the load increments available (50, 100, and 200 g).

Figure 3. Example wearable resistance load placements for (A) the thigh wearable resistance experimental condition and (B) the shank wearable resistance experimental condition

A B



3.2.3 Data Analysis

Marker trajectory data was filtered by a fourth-order Butterworth low-pass digital filter at participant-specific cutoff frequencies (13-18 Hz) via residual analysis performed on a tibia-mounted marker [105]. The data were modelled using the UWA lower-limb model [7], modified to be compatible with the adjusted marker sets. All data modelling was performed using Vicon Nexus 2 (Vicon, Oxford Metrics, Oxford, UK). Modelled kinematic outputs were exported from Vicon Nexus 2 into CSV format and imported in MATLAB (MATLAB R2019b, The MathWorks, Inc., Natick, Massachusetts, USA) for post-processing and feature extraction. A custom algorithm was developed to extract the joint angle vector data associated with the sagittal plane of movement, specifically hip flexion and extension, knee flexion and extension, and ankle dorsiflexion angles, for the stride cycles of interest. The stride cycles commencing from the start of the first and third ground contacts on the track after clearing the starting blocks were identified for each athlete's trials and used for the analysis. For each stride, the peak hip flexion and extension, knee flexion and extension, and ankle dorsiflexion angles were identified for the limb that made first ground contact. Therefore, data from only one limb was used for the analysis. The angles corresponded with the late stance phase (i.e. peak hip and knee extension), late swing phase (i.e. peak hip and knee flexion), and the early-mid stance phase (i.e. peak ankle dorsiflexion). The average flexion and extension velocities were calculated for the hip and knee joints across each stride from the time points of peak joint angle values (e.g. hip extension velocity was calculated from the time point of peak hip flexion to peak hip extension). The average ankle joint dorsiflexion velocity was calculated from the onset of dorsiflexion at the start of the stance phase to the time point of peak dorsiflexion, thus corresponding to the weight acceptance portion of the early-mid stance phase. To represent average athlete performance for each sprint condition, the mean values for all dependent variables across the two trials were used for statistical analysis.

3.2.4 Statistical Analysis

Athletes that were only able to attend one testing session due to scheduling conflicts were included in the analysis of the testing session in which they participated. A paired-samples t-test was used to test for differences between the thigh and unloaded conditions (n = 14) and between the shank and unloaded conditions (n = 15). For the athletes that attended both testing sessions (n = 11), a paired-samples t-test was also used to test for differences between the thigh and shank loaded conditions. The between condition difference scores were inspected for normality and outlier data samples. Outliers classified as extreme (>3 box-lengths from the edge of the boxplot) or those that prevented a normal distribution (assessed by Shapiro-Wilk's test) were removed from the final analysis. Marker failure resulted in missing angle data at the knee and ankle for the thigh testing session (n = 1 and 2, respectively) and the shank testing session (n = 1 and 2, respectively). Analyses were performed using SPSS Statistics (Version 25, IBM, Armonk, NY, USA). Significance was set at $p \leq 0.05$. ES statistics (Cohen's d) were calculated and described as trivial (<0.20), small (0.20), moderate (0.50) and large (0.80) [21].

3.3 Results

The 10 m sprint times increased with thigh WR by a mean difference of 0.02 s compared with unloaded sprinting (unloaded = 2.16 ± 0.09 s and loaded = 2.18 ± 0.08 s, ES = 0.24, p = 0.13). Shank WR significantly increased 10 m sprint times by a mean difference of 0.03 s compared with unloaded sprinting (unloaded = 2.15 ± 0.09 s and loaded = 2.18 ± 0.09 s, ES = 0.33, p = 0.02).

All group-averaged changes to peak joint angles with thigh and shank WR were classified as trivial or small (ES = 0.00–0.38) and < ± 2°. The peak joint angles for each experimental condition are presented in Table 3 and Table 4. With thigh WR, significantly less hip flexion occurred at the end of the forward swing phase during stride 1 and stride 3 and significantly less knee extension occurred at the end of the stance phase during stride 3 compared with unloaded sprinting (ES = 0.27–0.32). With shank WR, significantly less hip flexion occurred at the end of the forward swing phase during stride 1 and significantly less hip extension occurred at the end of the stance phase during stride 3 compared with unloaded sprinting (ES = 0.23–0.38). A visual display of the individual response to each experimental condition for the peak hip and knee joint angles is given in Figure 4. With the exception of hip flexion, where the majority of athletes responded to the WR loading by reaching smaller peak hip flexion angles at the end of the forward swing, no clear trends in individual responses were identified across both strides within

Table 3. Peak joint angle and average velocity of the hip, knee, and ankle for the unloaded and thigh wearable resistance conditions during the first and third stride of sprint acceleration

	Peak Joint Angle (°)				Average Velocity (°/s)			
	Unloaded	Thigh-loaded	Difference	Effect Size	Unloaded	Thigh-loaded	Difference	Effect Size
Stride 1								
Hip Extension	3.35 ± 5.18	4.07 ± 4.86	0.72	0.14	–360 ± 26.0	–343 ± 30.5*	16.6	0.60
Hip Flexion	98.7 ± 5.04	97.0 ± 5.56*	–1.81	–0.32	445 ± 37.6	423 ± 39.4*	–22.6	–0.57
Knee Extension	17.8 ± 5.78	18.3 ± 5.11	0.47	0.09	–311 ± 30.1	–301 ± 24.8*	10.8	0.36
Knee Flexion	126 ± 7.75	125 ± 10.2	–0.82	–0.11	657 ± 50.3	648 ± 65.0	–8.44	–0.16
Ankle Dorsiflexion	30.0 ± 5.98	29.2 ± 5.41	–0.81	–0.14	168 ± 41.5	160 ± 38.7	–8.11	–0.20
Stride 3								
Hip Extension	–3.20 ± 4.87	–2.15 ± 4.83	1.05	0.22	–422 ± 28.2	–407 ± 24.5*	14.8	0.57
Hip Flexion	98.0 ± 6.43	96.4 ± 5.28*	–1.53	–0.27	459 ± 41.8	442 ± 37.9*	–16.8	–0.43
Knee Extension	15.0 ± 5.40	16.8 ± 5.86*	1.81	0.32	–381 ± 37.7	–354 ± 39.6*	26.7	0.70
Knee Flexion	136 ± 7.93	134 ± 9.32	1.33	–0.23	736 ± 53.0	722 ± 47.3	14.6	–0.28
Ankle Dorsiflexion	28.8 ± 4.26	28.5 ± 5.11	0.24	–0.06	232 ± 30.5	232 ± 35.2	0.89	0.00

Note: Values reported as mean ± standard deviation, Difference score reported as mean difference of the thigh-loaded – unloaded conditions, * = significantly different from the unloaded condition at $p \leq 0.05$.

Table 4. Peak joint angle and average velocity of the hip, knee, and ankle for the unloaded and shank wearable resistance conditions during the first and third stride of sprint acceleration

	Peak Joint Angle (°)				Average Velocity (°/s)			
	Unloaded	Shank-loaded	Difference	Effect Size	Unloaded	Shank-loaded	Difference	Effect Size
Stride 1								
Hip Extension	1.46 ± 6.81	1.60 ± 6.90	0.14	0.02	–368 ± 23.5	–359 ± 22.3*	8.64	0.39
Hip Flexion	99.5 ± 4.16	97.8 ± 4.85*	–1.76	0.38	454 ± 39.2	445 ± 41.5*	–8.76	0.22
Knee Extension	12.5 ± 6.23	12.2 ± 5.66	–0.27	0.05	–340 ± 44.3	–335 ± 34.7	4.79	0.13
Knee Flexion	129 ± 7.99	129 ± 6.53	–0.21	0.00	686 ± 85.9	694 ± 64.5	7.69	0.11
Ankle Dorsiflexion	28.9 ± 3.82	29.9 ± 4.16	0.97	0.25	178 ± 47.3	192 ± 43.5	13.6	0.31
Stride 3								
Hip Extension	–5.31 ± 6.48	–3.98 ± 5.14*	1.33	0.23	–432 ± 28.1	–418 ± 28.4*	14.4	0.50
Hip Flexion	98.3 ± 4.52	97.2 ± 5.17	–1.05	0.23	466 ± 39.1	450 ± 31.4*	–15.5	0.45
Knee Extension	11.7 ± 6.38	11.9 ± 6.76	0.20	0.03	–402 ± 57.0	–394 ± 41.9	7.57	0.16
Knee Flexion	136 ± 4.43	137 ± 5.13	1.72	0.21	740 ± 56.4	763 ± 58.8*	23.4	0.40
Ankle Dorsiflexion	28.8 ± 4.08	29.1 ± 2.93	0.29	0.09	244 ± 34.1	242 ± 35.3	–1.59	0.06

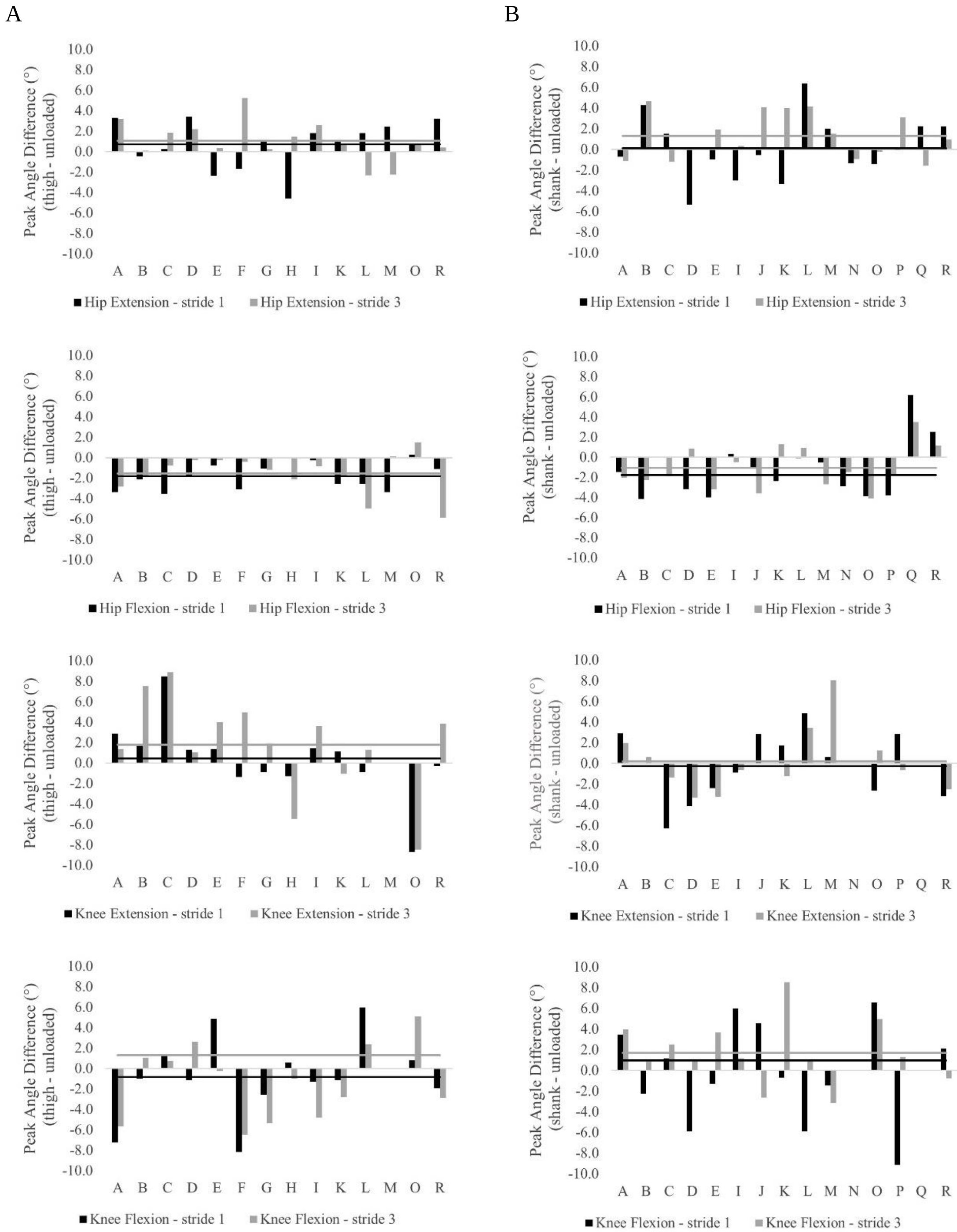
Note: Values reported as mean ± standard deviation, Difference score reported as mean difference of the shank-loaded – unloaded conditions, * = significantly different from the unloaded condition at $p \leq 0.05$.

an experimental condition (i.e. stride 1 versus stride 3) or between experimental conditions (i.e. thigh versus shank WR).

All group-averaged changes in angular velocity ranged from trivial to moderate with thigh WR (ES = 0.00–0.70) and shank WR (ES = 0.06–0.50) across stride 1 and 3. The average angular velocities for each experimental condition are presented in Table 3 and Table 4. Thigh WR significantly reduced hip and knee extension velocity and hip flexion velocity during stride 1 and 3 compared with unloaded sprinting (ES = 0.43–0.70). Shank WR significantly reduced hip extension and flexion velocity during stride 1 and 3 and significantly increased knee flexion velocity during stride 3 compared with unloaded sprinting (ES = 0.22–0.50).

When comparing the thigh versus the shank loaded conditions, with thigh WR, athletes reached significantly less knee extension at the end of the stance phase during stride 1 by a mean difference of 4.34 ± 6.17° (ES = 0.73, $p = 0.05$). Also, with thigh WR, the average knee extension and ankle dorsiflexion velocities were significantly slower during stride 1 by 30.8 ± 25.1°/s (ES = 0.93, $p < 0.01$) and 29.1 ± 38.7°/s (ES = 0.70, $p = 0.05$), respectively.

Figure 4. Individual difference scores (loaded – unloaded) for the thigh WR (column A) and shank WR (column B) experimental conditions. Group average difference scores represented with the horizontal lines



Note: Values are organised by the athlete. A positive difference score means a decrease in hip extension, while a negative difference score means a decrease in knee extension, hip flexion, and knee flexion for the loaded condition. Horizontal lines indicate the group mean difference score for stride 1 (black) and stride 3 (grey). No knee data was available for athlete M in the thigh WR experimental condition and athlete N and Q in the shank WR experimental condition due to marker failure.

3.4 Discussion

This study determined the effect of 2% BM WR placed on two different lower-limb segments (thigh and shank) on hip, knee, and ankle joint kinematics during the early acceleration phase of sprint running. The hypothesis that any significant changes to the peak joint angles would be of a small effect and any significant changes to angular velocity would be classified as small or moderate was supported. The main findings were: 1) increases to 10 m sprint times were small with thigh WR (ES = 0.24), and with shank WR the increase was also small but significant (ES = 0.33); 2) significant differences in peak joint angles between the unloaded and loaded conditions were small (ES = 0.23–0.38), limited to the hip and knee joints, and < 2° on average; 3) aside from peak hip flexion angles, no clear trends were observed in individual difference scores between the loaded and unloaded conditions for peak joint angles; and, 4) thigh and shank WR produced similar reductions in average hip flexion and extension angular velocities, while thigh WR decreased average knee extension velocity and shank WR increased average knee flexion velocity compared with unloaded sprint running (all < ± 27°/s, ES = 0.22–0.70, $p < 0.05$).

Lower-limb WR has been purported as a movement- and speed-specific training option for sprint running [31,36,56] and initial evidence appears to favour training with WR compared to training with no load for maintaining [35] and improving sprint running performance [12]. However, it is important to ascertain if global changes to movement speed when loaded maintain specificity to the maximal speeds associated with sprint running. In this study, sprint running with WR increased 10 m sprint times by < 1.5%. This indicates that the athletes were moving at near maximal acceleration speeds through the early acceleration phase under resistance. This is similar to changes reported previously where thigh and shank WR of ≤ 2% BM has been shown to affect sprint running speed and time measures by 0.9–2.23% (ES = 0.22–0.55) [48,59,61,107]. These measures were taken across early acceleration to maximal velocity, with the largest changes occurring at maximal velocity [48,59,61,107]. In the current study, the significant increase to sprint time occurred when the WR was placed on the shank, which corresponded to the experimental condition with the greater rotational overload about the hip given the increased distance between this joint and the applied load. A method to increase the rotational overload with WR, therefore, is to move the load distally from the primary joint axis of rotation [31]. As a result, the same load magnitude moved from the thigh to the shank will create a greater rotational overload about the hip joint and additionally overload the knee joint during sprinting.

The athletes in this study were able to achieve similar ranges of motion to unloaded sprint running with thigh or shank WR with all changes to peak joint angles < ± 2°. These findings confirm that the WR loading schemes deployed in this study do not produce appreciably different movement patterns across the early acceleration phase of sprint running. However, it is important to note the variation in individual responses. Other than the exception of hip flexion, where the majority of athletes responded to the WR loading by reaching smaller peak hip flexion angles at the end of the forward swing phase, no clear trends in responses to a WR condition can be observed. Additionally, the effects for some athletes were upwards of ± 8°. Given the clear variation in individual responses (direction and magnitude), coaches are encouraged to assess the acute effects of lower-limb WR loading on their athletes on an individual basis to determine whether the addition of the WR is having the desired effect for the individual's training needs. Research continuing in this topic may consider kinematic waveform analysis to provide a more complete analysis across the entire stride and further context for discrete variable analysis.

The effect of WR loading had a greater overall influence on the average angular velocities than the average peak joint angles of the lower-limb joints with significant changes from unloaded sprint running considered small to moderate. This highlights the specific overload to the speed of the stride cycle (i.e. stride frequency) that occurs with this resistance training method. The stride cycle of sprint running encompasses open kinetic-chain and closed kinetic-chain movements for the joints of the lower-limb, the swing and stance phases, respectively. With thigh WR, the significant overload to the average hip joint velocity occurred during the open kinetic-chain (hip flexion) and closed kinetic-chain (hip extension) portions of the movement. However, the significant overload to the average knee joint velocity only occurred during knee extension which primarily occurs during the closed kinetic-chain portion of the stride cycle. Considering, there was no load placed distal to the knee joint in the thigh loaded condition, it would be expected the that the knee joint wouldn't experience significant changes to the measures associated with the swing phase. With shank WR, athletes responded similarly at the hip joint, i.e. the velocity at the hip joint was significantly decreased during the open kinetic-chain and closed kinetic-chain portions of the stride cycle. However, shank WR did not significantly alter the average knee or ankle velocities during the closed kinetic-chain portion of the stride cycle (i.e. knee extension and ankle dorsiflexion). Thus, the athletes did not experience the knee extension overload during stance that was evident in the thigh loaded condition. Further, there were no consequent effects further down the chain at the ankle joint even though the shank load placement was proximal to the joint. Conversely, athletes increased average knee flexion velocity ($p < 0.05$ at stride 3) during the forward swing phase. The increased average knee flexion velocity at stride 3 coincided with a greater peak knee flexion angle (by 1.72°, ES = 0.21, $p > 0.05$). This may indicate a kinematic mechanism to reduce the rotational inertia about the hip joint in an effort to maintain swing phase timing and have the limb prepared for next touchdown.

The findings of this study further highlight the movement-specificity of placing the WR load on the lower-limbs compared to other load placement options, such as the torso with vest loading, for sprint running. With lower-limb placed WR, the resistance must be overcome during both the open and closed kinetic-chain portions of the movement pattern, whereas a specific lower-limb overload is only incurred during the closed kinetic-chain portion of the movement pattern with vest loading. Recent research has demonstrated a strong correlation between running speed and thigh angular velocity during both the swing and ground contact phases of the stride cycle during upright running [20]. Thus, training should work to produce adaptations to both the flexion and extension actions to support the necessary reciprocal action of the thighs and contribute to the vertical forces necessary to produce faster running speeds [20]. Given that both shank and thigh WR reduced the average angular velocities about the hip joint, programmatic use of lower-limb WR may be a method to develop the speed-specific strength associated with the fast flexion and extension actions at hip joint during sprint running.

Although it was not the primary purpose of this study, 11 of the athletes participated in both the thigh and shank loaded testing sessions. Direct comparison between the two loaded conditions (i.e. thigh versus shank loading) revealed that with thigh WR, athletes performed less knee extension at the end of the stance phase and average knee extension and ankle dorsiflexion velocities were slower ($p \leq 0.05$, ES = 0.70–0.93). However, these effects were limited to stride 1. These findings provide further insights to the effects of thigh- and shank-placed WR on sprint running, which in tandem with future research, can be used to better inform WR placement.

A limitation to this research is that only a snapshot of the joint kinematics (i.e. 2 strides) during early acceleration were able to be included due to motion capture volume limitations. It is unknown how the joint kinematics of the remainder of the acceleration phase compares to unloaded sprint running. Additionally, the athletes that participated in this study were not familiarised to lower-limb WR outside of what was provided for this study. It is unknown how the joint kinematics when sprint running with WR might change following repeated exposure to lower-limb WR. Similarly, the kinematic adaptations that occur following sprint running training with lower-limb WR requires investigation.

3.5 Conclusion

Sprint running with 2% BM thigh and shank WR produced small changes to 10 m sprint times (< 1.50%; ES = 0.24–0.33) and lower-limb joint angles (all < 2° on average; ES = 0.23–0.38). It appears that lower-limb wearable resistance of ≤ 2% BM does not significantly disrupt the movement patterns associated with sprint running, however, individual responses will likely vary and can be considered on a case-by-case bases to determine whether the addition of the WR is having the desired effect for the individual’s training needs. The effect of WR loading had a greater overall influence on angular velocity compared to the influence on the peak joint angles at the hip and knee joints with significant changes considered small to moderate (≤ ± 27°/s, ES = 0.22–0.70). This highlights the specific overload to the movement speed of the stride cycle that occurs with this training method. Further, the significant overload to hip flexion and extension velocity with both thigh and shank-placed WR may be especially helpful to target the flexion and extension actions associated with fast sprint running.

Chapter 4. Changes to Horizontal Force-Velocity and Impulse Measures During Sprint Running Acceleration with Thigh and Shank Wearable Resistance

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Feser EH, Bezodis N, Neville J, Macadam P, Uthoff AM, Nagahara R, Tinwala F, Clark K, Cronin JB. Changes to horizontal force-velocity and impulse measures during sprint running acceleration with thigh and shank wearable resistance. [published online ahead of print, 2021 Feb 14]. *J Sports Sci*. 2021;1-9. doi: 10.1080/02640414.2021.1882771.

Author contributions: Feser 80%, Bezodis 4%, Neville 4%, Macadam 2%, Uthoff 2%, Nagahara 2%, Tinwala 2%, Clark 2%, and Cronin 2%

4.0 Prelude

A main finding in Chapter 2 was that researchers had yet to directly measure ground reaction force production during overground sprint running with WR and that the one report of direct measures (completed with an instrumented treadmill) failed to quantify the features of horizontal force production related to sprint running performance during acceleration, e.g. propulsive impulse. Additionally, in Chapter 2 it was found that only a minimal number of loading magnitudes (i.e. 3% and 5% BM) and placements (i.e. whole limb) had been investigated by researchers studying the kinetics of wearable resistance. In addition, minimal differences in early acceleration kinematics when sprint running with 2% thigh WR compared to 2% shank WR were observed in Chapter 3. However, any differences in the underlying production of forces with thigh and shank WR remained unknown. Therefore, the purpose of this chapter was to determine the effect of two different WR placements (i.e. thigh versus shank) on horizontal F-v and impulse measures during sprint running acceleration. This information helps coaches and strength and conditioning practitioners better understand what mechanical components can be influenced by lower-limb WR in an attempt to produce positive sprint running performance adaptations over time.

4.1 Introduction

Sprint running is an important facet of many sports and the interest in understanding the mechanics of sprint running is evident by the extent of scientific literature addressing this topic [43,69]. Mechanically, faster sprint running is determined by the athlete's technical ability (supported by sufficient strength and metabolic capacity) to produce high force production directed horizontally during acceleration [23,71] and maintain high vertical support forces as contact times decrease during maximal velocity sprint running [104]. A deeper understanding of the mechanics of sprint running can be provided by evaluating kinetic information such as mechanical output characteristics (e.g. horizontal F-v profile) [93]; magnitude and duration of force application (i.e. impulse) [80]; and identifying the relationship between horizontal force to total force with increasing speed (i.e. ratio of forces) [71]. These kinetic factors provide an understanding of the underlying causes of sprint running performance and, thereby, offer pertinent information to be considered when reviewing and attempting to more thoroughly understand a training method's potential as a stimulus to generate improvements in sprint running performance.

Lower-limb wearable resistance (WR) training involves attaching "micro-loads" (e.g. 1–3% of BM) to the lower-limb(s) of the body. The load is worn during sport-specific movement training as an application of the principle of training specificity. Based on this principle, training should replicate the characteristics of the sporting activity so any metabolic or mechanical adaptations will transfer directly to the performance of the movement itself. These contentions have formed the basis for using lower-limb WR as a training method for sprint running with the ultimate goal of improving sprint running performance [36,54,56]. An important consideration of using lower-limb WR is whether such loading influences sprint running kinetics. However, the influence of lower-limb WR on sprint running kinetics is not well understood.

Sprint running with lower-limb WR has been shown to alter the horizontal F-v profile, which provides insight into an athlete's ability to generate horizontal force from zero to their theoretical maximal velocity (V_0). While the optimal profile for sprint running may vary based on sport-specific needs [44,50], it has been established that faster short-distance sprint running is significantly correlated to the athlete's ability to maintain horizontal force production with increasing velocity and produce high levels of horizontal force and net horizontal power during each step [71]. When 3% BM WR was attached to the thigh and shank (thigh+shank) during overground sprint running, a ~10% more force dominant F-v profile was observed [55,99]. This profile change resulted from a reduction in V_0 and an increase in relative theoretical maximal horizontal force (F_{0SM}; relative to system mass; 5.08–6.25%) with little corresponding change to total sprint running time [55,99]. The time to sprint the 20 m distance used in these studies increased by 0.58% to 1.40% compared to unloaded sprint running. However, the same changes were not found when greater mass (5% BM) was attached to the thigh+shank during sprint running; sprint times over 20 m were significantly slower (−2.02%) and F_{0SM} only increased by 1.25% [99]. It would seem that different loading magnitudes may have varying effects and that more resistance does not always equate to more horizontal force production when using lower-limb WR during short-distance sprint running. It needs to be noted, however, that only a minimal number of loading magnitudes (i.e. 3% and 5% BM) have been investigated to date with no F-v profile information available on the effect of the WR placed solely on the shank.

Sprint running with lower-limb WR has also been shown to change the impulses generated during the acceleration phase of sprint running [61]. During unloaded sprint running, relative propulsive ($IMP_{P(BM)}$) and net anterior-posterior (IMP_{AP}) impulses have shown to significantly correlate (r = 0.52–0.87) to overground sprint running velocity [47], 40 m acceleration performance [75], and 10 m sprint time [51] with relative braking ($IMP_{B(BM)}$) and vertical impulses (IMP_{V}) having a corresponding weak or non-significant correlation (r = 0.04−0.50). However, sufficient vertical impulse is necessary to maintain upright body position when in contact with the ground and to elevate the body for the next flight phase; also, any increases in braking impulse must be met with an increase in propulsive impulse to maintain a given velocity. With 2% BM thigh WR, $IMP_{AP(SM)}$ has been shown to significantly decrease (−4.73%) during the acceleration phase of a 50 m sprint, which corresponded to a non-significant increase in $IMP_{B(SM)}$ (8.08%) and decrease in $IMP_{P(SM)}$ (−1.52%) [61]. It would appear that 2% thigh WR alters the interplay of propulsive and braking forces during ground contact of the acceleration phase. These findings provide insight into how lower-limb WR may affect impulse production during sprint running and therefore assist in evaluating lower-limb WR as a training stimulus. However, these impulse values were averaged over steps 5−14 of the acceleration phase. A more detailed investigation of acceleration mechanics is warranted considering kinetic determinants of performance have been shown to shift as velocity increases [80]. It is also unknown if similar effects on impulse would occur with other lower-limb WR placements.

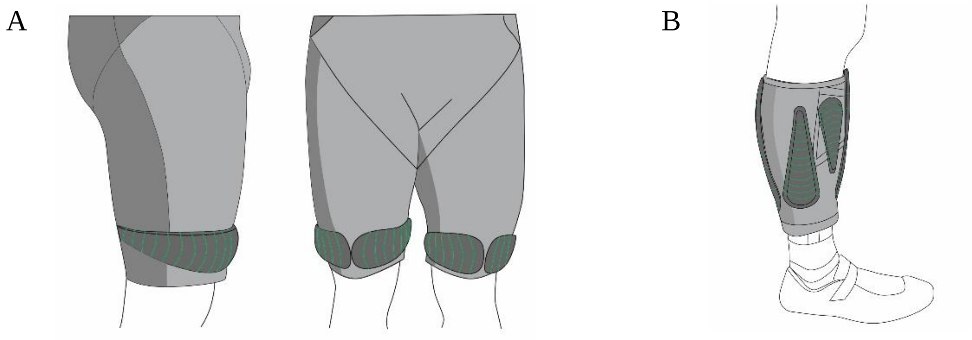
Researchers have started to uncover how lower-limb WR may alter horizontal F-v mechanical variables and impulse production during sprint running but further investigation is needed for coaches to better understand how to optimise lower-limb WR use to produce desired training adaptations. The information available to date is limited with minimal kinetic analyses that have only utilised two load placements (thigh and thigh+shank). Further information on how athletes respond to different load placements and how this affects the kinetics of sprint running is necessary. In particular, it is of interest to determine the effect of the same load magnitude placed on the thigh versus the shank as the more distal load placement produces a greater rotational overload (moment of inertia) to the lower-limb with the same load magnitude. This information will help coaches and strength and conditioning practitioners better understand what mechanical components can be influenced by lower-limb WR in an attempt to produce positive sprint running performance adaptations over time. Therefore, the purpose of this study was to determine the effect of two different WR placements (i.e. thigh versus shank) on horizontal F-v and impulse measures during sprint running acceleration. It was hypothesised that greater changes to the horizontal F-v and impulse measures would occur with shank WR due to the greater inherent rotational inertia.

4.2 Methods

4.2.1 Experimental Procedures

Eleven male athletes volunteered to participate in this study (mean ± standard deviation; age = 21.2 ± 2.56 years, body mass = 69.1 ± 3.95 kg, stature = 1.75 ± 0.05 m). The athletes were university level, sprint specialists with a 100 m best time of 11.34 ± 0.41 s (range = 10.70–11.92 s) and sprint training experience of 9.73 ± 2.90 years (range = 7–16 years). Written informed consent was obtained before study participation. All study procedures were approved by the host University Institutional Review Board. The athletes reported to the testing facility on two occasions separated by a minimum of 72 hours. Upon arrival, the athletes completed a self-selected warm-up that included running drills, dynamic stretching, and a series of submaximal (e.g. 50%, 75%, and 90% of maximal effort) sprints. Following this, each athlete completed four maximal effort 50 m sprints that consisted of two repetitions under each experimental condition - loaded (WR attached to the thigh or shank) and unloaded (no WR). The sprints were completed in a randomised order separated by a minimum of five minutes of passive rest and each started from starting blocks. The thigh and shank WR experimental conditions were randomly assigned between the two testing occasions (i.e. each athlete completed two shank WR and two unloaded sprints during one session, and two thigh WR and two unloaded sprints during the other session). The athletes wore Lila™ Exogen™ (Sportboleh Sdh Bhd, Kuala Lumpur, Malaysia) weighted compression shorts or calf sleeves for the thigh and shank loaded trials, respectively. These specialised compression garments allow for Velcro backed "micro-loads" to be attached to the garment in a variety of different orientations and locations. The thigh WR was attached with a horizontal orientation on the distal aspect of the thigh with 2/3 of the load placed more anteriorly and 1/3 placed more posterior following previous thigh WR research [59,61] (Figure 5A). The shank WR was attached in line with the long axis of the shank, equally encircling the shank (Figure 5B). A 2% BM load magnitude was used for each loaded trial (i.e. 1% BM attached to each limb) following previous research [59,61]. Due to the loading increments available (100, 200, and 300 g), exact loading magnitudes ranged from 1.92–2.01% BM. All sprint trials were completed on an indoor athletic track surface (Hasegawa Sports Facilities Co., Hasegawa, Japan) with the athletes wearing their spiked running shoes. The sprint start was signalled with an electronic starting gun (Digi Pistol, Molten, Hiroshima, Japan). A series of 54 in-ground force platforms (TF-90100, TF-3055, TF-32120, Tec Gihan, Uji, Japan) were used to measure ground reaction forces (GRF) at 1000 Hz for a total distance of 52 m spanning from 1.50 m behind the starting line to the 50.5 m mark.

Figure 5. Example wearable resistance load placements for (A) the thigh wearable resistance experimental condition and (B) the shank wearable resistance experimental condition



4.2.2 Data Processing

GRF data were filtered using a fourth-order Butterworth low-pass digital filter with a cut-off frequency of 50 Hz. Touch-down and take-off detection were identified in the filtered data by a 20 N vertical GRF threshold. The data from the initial movement in the blocks to the step at maximal velocity was used for the analysis. Horizontal centre of mass (COM) velocity (V_H, as a function of time) was calculated from the initial movement to maximal velocity per the methods outlined by Colyer, Nagahara, and Salo [22]. Per this method, the impulse-momentum relationship was used to determine instantaneous V_H throughout the entire sprint from the IMP_{AP} and estimated aerodynamic drag [93]. The V_H was modelled with a mono-exponential fit and a series of horizontal F-v mechanical variables were calculated from the linear F-v relationship, the second-degree polynomial power-velocity relationship, and the linear relationship between the ratio of horizontal to total force and V_H for each trial [93]. These variables were used to describe the general mechanical ability of the athlete to produce horizontal external force during sprint running and included: V_0, F_0, P_{max}, maximal ratio of force (RF_{max}), and index of force application (D_{RF}) [74]. These horizontal F-v mechanical variables, along with the slope of the F-v profile ($S_{FV(BM)}$; $-F_{0(BM)}/V_0$), were calculated consistent with the method previously validated [74,93]. Further, sprint times (5, 10, 20, and 30 m) were derived from the integral of the V_H data. The maximal velocity (V_{max}) was determined from the step with the maximal toe-off velocity. The exponential modelling of the V_H data was well fit with all $R^2 > 0.99$.

The steps at 5 m, 10 m, 20 m, and 30 m were extracted to identify changes in impulse between the unloaded, thigh, and shank conditions. This was implemented by identifying the step in which the athletes' COM location at toe-off was closest to the metre mark of interest. Intra-individual consistency was ensured by using the same step for all trials. The step used for each condition along with the corresponding time, distance, and velocity at toe-off are reported in Table 5. This comparative approach was chosen since many coaches prescribe training repetitions based on set linear distances and pilot data suggests that athletes finish acceleration earlier when sprint running with WR. Impulse values were calculated by time integration of the respective directional component of force. Impulse values are reported as both absolute and normalised to BM.

Table 5. Mean and standard deviation for time, distance, velocity, percent of maximal velocity and the step number used at each distance of interest for the unloaded, thigh, and shank conditions' distance-matched steps

		Step (#)	Time at toe-off (s)	Distance at toe-off (m)	Velocity at toe-off (m·s^{-1})	Percent of max toe-off velocity (%)
5 m	**U**	3 (n = 2), 4 (n = 8), 5 (n = 1)	1.27 ± 0.07	4.96 ± 0.43	6.47 ± 0.31	69.5 ± 2.10
	T		1.28 ± 0.09	5.00 ± 0.44	6.45 ± 0.27	70.6 ± 2.61
	S		1.29 ± 0.08	5.00 ± 0.39	6.40 ± 0.28	71.1 ± 2.28
10 m	**U**	6 (n = 2), 7 (n = 7), 8 (n = 2)	1.98 ± 0.09	9.94 ± 0.44	7.79 ± 0.30	83.7 ± 1.25
	T		1.99 ± 0.09	9.91 ± 0.40	7.70 ± 0.28	84.4 ± 1.32
	S		2.00 ± 0.09	9.91 ± 0.37	7.64 ± 0.30	84.9 ± 1.70
20 m	**U**	11 (n = 2), 12 (n = 4), 13 (n = 3), 14 (n = 2)	3.21 ± 0.13	20.1 ± 0.42	8.87 ± 0.36	97.1 ± 1.64
	T		3.23 ± 0.14	20.1 ± 0.54	8.70 ± 0.32	95.3 ± 0.94
	S		3.26 ± 0.15	20.1 ± 0.46	8.64 ± 0.37	96.0 ± 1.00
30 m	**U**	16 (n = 2), 17 (n = 4), 18 (n = 3), 19 (n = 2)	4.33 ± 0.17	30.2 ± 0.65	9.23 ± 0.39	99.1 ± 0.39
	T		4.39 ± 0.15	30.3 ± 0.46	9.07 ± 0.37	99.4 ± 0.27
	S		4.42 ± 0.17	30.2 ± 0.26	8.95 ± 0.43	99.5 ± 0.37

Note: U = unloaded condition, T = thigh condition, S = shank condition.

4.2.3 Statistical Analysis

To represent each athlete's performance for each experimental condition, the data from the two trials for each loaded condition and the four trials for the unloaded condition were averaged. A series of preliminary analyses (paired-samples t-tests) were used to confirm there were no significant differences in sprint times between the two testing sessions for the unloaded condition before averaging the four trials (all $p > 0.05$). To determine the effect of thigh and shank WR on sprint times, mechanical output, and impulse, a one-way repeated measures ANOVA with pair-wise post hoc comparisons (Fisher's LSD) were conducted. An outlier was defined as a value greater than 3 box-lengths from the edge of the box in the IMP_{AP} 10 m, IMP_{B} 5 m and 20 m, and $IMP_{B(BM)}$ 20 m and 30 m data sets and in such cases was removed from the analysis. The differences between measures were normally distributed as assessed by Shapiro-Wilk's test ($p > 0.05$). Analyses were performed using SPSS Statistics (Version 26, IBM, Armonk, NY, USA). Significance was set at $p \le 0.05$. ES statistics (Cohen's *d*) were calculated as the mean of the within-subjects difference scores divided by the average standard deviation of both repeated measures [53] and described as trivial (<0.20), small (0.20), moderate (0.50) and large (0.80) [21]. To describe individual responses to each loaded condition, the smallest worthwhile change (SWC) was calculated as 0.2 × pre-intervention between-subject standard deviation. Each response was then classified as an increase (> + SWC) or decrease (> – SWC) for each dependent variable if the absolute change from the unloaded condition was outside of the SWC, and a trivial change if it remained within the SWC [21].

4.3 Results

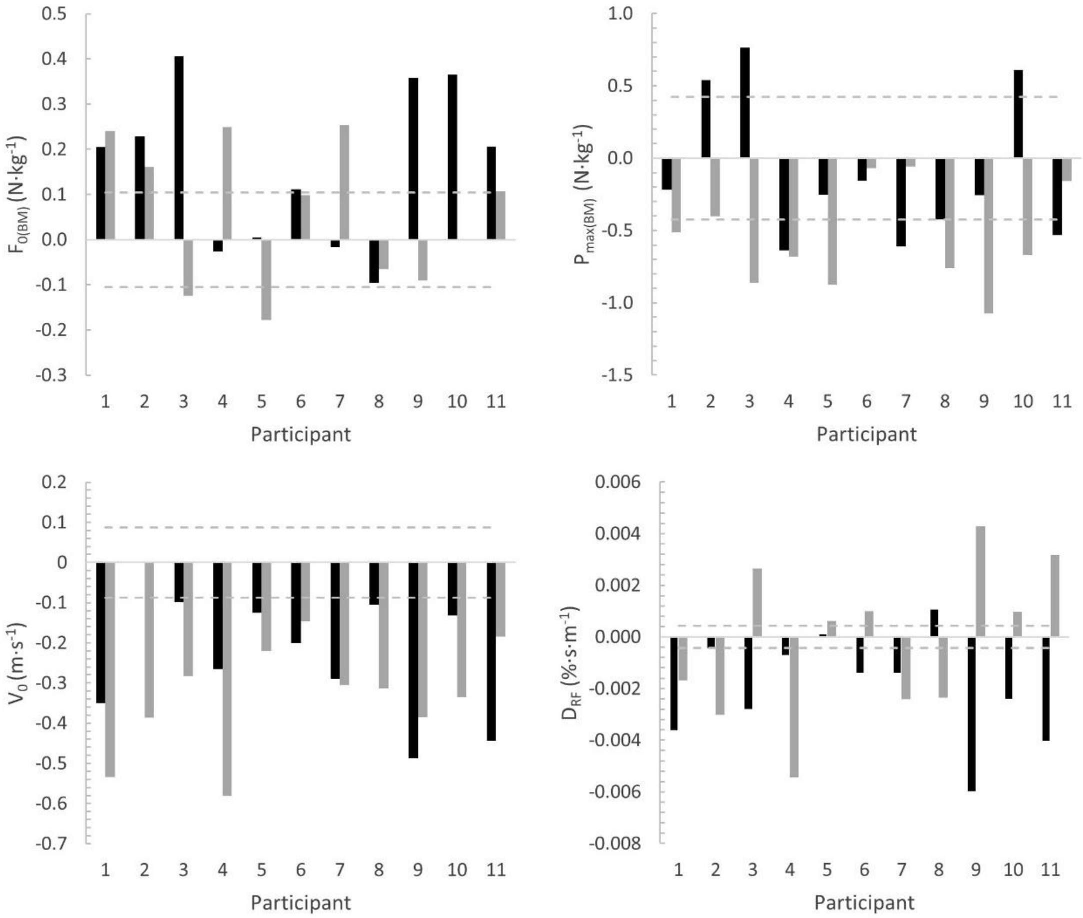
Sprint running times, maximal velocity, and horizontal F-v variables with post-hoc *p*-value and effect size statistics are presented in Table 6. Sprint running with thigh WR significantly increased 10 m, 20 m, and 30 m sprint times and decreased V_{max} (ES = 0.21–0.48), whilst sprint running with shank WR significantly increased all sprint times and decreased V_{max} (ES = 0.46–0.76). Sprint running with thigh WR significantly increased F_0 (ES = 0.32) and D_{RF} (ES = 0.78) and decreased V_0 (ES = 0.54), resulting in a more force dominant $S_{FV(BM)}$ (ES = 1.12). Sprint running with shank WR significantly increased D_{RF} (ES = 0.86) and decreased $P_{max(BM)}$ (ES = 0.26), V_0 (ES = 0.73) and RF_{max} (ES = 0.34), also resulting in a more force dominant $S_{FV(BM)}$ (ES = 1.23). When comparing thigh versus shank WR, 10 m, 20 m, and 30 m sprint times were significantly slower and $P_{max(BM)}$ and V_{max} (ES = 0.21–0.33) were significantly less with shank WR. The individual response to thigh and shank WR for $F_{0(BM)}$, $P_{max(BM)}$, V_0, and D_{RF}, reported as the absolute change from the unloaded condition (i.e. WR – unloaded), are presented in Figure 6. With thigh WR, the majority of athletes increased $F_{0(BM)}$ (7/11) and decreased V_0 (10/11), but for $P_{max(BM)}$ and D_{RF} a mixed response was observed. With shank WR, the majority of the athletes decreased $P_{max(BM)}$ (7/11) and all athletes decreased V_0, whilst a mixed response was observed for $F_{0(BM)}$ and D_{RF} measures.

Table 6. Mean and standard deviation for sprint running times, maximal velocity, and horizontal force-velocity variables for each sprint running condition with post-hoc *p*-value and effect size (ES) statistics

	Unloaded	**Thigh**	**Shank**	**Thigh - Unloaded**	**Shank - Unloaded**	**Thigh - Shank**
	$\bar{x}$ (SD)	**$\bar{x}$ (SD)**	**$\bar{x}$ (SD)**	***p*-value; ES**	***p*-value; ES**	***p*-value; ES**
5 m time (s)	1.28 ± 0.04	1.28 ± 0.05	1.30 ± 0.05	0.07; 0.00	<0.01*; 0.44	0.06; 0.40
10 m time (s)	1.98 ± 0.07	2.00 ± 0.07	2.02 ± 0.07	0.02*; 0.29	<0.01*; 0.57	0.03*; 0.29
20 m time (s)	3.19 ± 0.11	3.22 ± 0.12	3.25 ± 0.12	0.01*; 0.26	<0.01*; 0.52	0.04*; 0.25
30 m time (s)	4.31 ± 0.16	4.36 ± 0.16	4.40 ± 0.17	<0.01*; 0.31	<0.01*; 0.55	0.04*; 0.24
V_{max} ($m \cdot s^{-1}$)	9.31 ± 0.40	9.13 ± 0.36	9.00 ± 0.44	<0.01*; 0.47	<0.01*; 0.74	0.03*; 0.33
F_0 (N)	583 ± 37.4	596 ± 42.7	585 ± 38.0	<0.01*; 0.32	0.51; 0.06	0.04; 0.27
$F_{0(BM)}$ ($N \cdot kg^{-1}$)	8.47 ± 0.52	8.62 ± 0.57	8.53 ± 0.53	0.01; 0.28	0.24; 0.11	0.24; 0.16
$P_{max(BM)}$ ($W \cdot kg^{-1}$)	20.3 ± 2.12	20.2 ± 2.06	19.7 ± 2.16	0.50; 0.05	<0.01*; 0.26	0.05*; 0.21
V_0 ($m \cdot s^{-1}$)	9.62 ± 0.44	9.39 ± 0.40	9.29 ± 0.47	<0.01*; 0.55	<0.01*; 0.73	0.09; 0.23
D_{RF} ($\% \cdot s \cdot m^{-1}$)	−7.82 ± 0.21	−8.02 ± 0.30	−8.04 ± 0.30	0.01*; 0.78	0.01*; 0.86	0.83; 0.07
RF_{max} (%)	55.2 ± 2.11	54.9 ± 2.19	54.5 ± 2.14	0.14; 0.13	<0.01*; 0.34	0.13; 0.20
$S_{FV(BM)}$ (%)	−0.88 ± 0.03	−0.92 ± 0.04	−0.92 ± 0.04	<0.01*; 1.14	<0.01*; 1.14	0.87; 0.00

Note: F_0 = theoretical maximal horizontal force; $F_{0(BM)}$ = theoretical maximal horizontal force relative to body mass; $P_{max(BM)}$ = peak power relative to body mass; V_0 = theoretical maximal velocity; D_{RF} = index of force application, RF_{max} = maximal ratio of force; $S_{FV(BM)}$ = slope of the force-velocity profile; * = significant post hoc comparison ($p \leq 0.05$) coinciding with a significant main test effect.

Figure 6. Absolute change in horizontal force-velocity mechanical variables from the unloaded condition with thigh (black) and shank (grey) wearable resistance for each participant



Note: Dashed lines indicate the smallest worthwhile change threshold (± 0.20 × unloaded condition between-subject standard deviation). $F_{0(BM)}$ = theoretical maximal horizontal force relative to body mass; $P_{max(BM)}$ = peak power relative to body mass; V_0 = theoretical maximal velocity; and D_{RF} = index of force application.

The absolute and relative impulse measures with post-hoc *p*-value and effect size statistics are shown in Table 7. In the anterior-posterior direction, thigh WR increased IMP_B and $IMP_{B(BM)}$ by small effects at 5 m, 10 m, and 30 m (ES = 0.29–0.38, $p > 0.05$) and large effects at 20 m (ES = 1.17–1.35, $p < 0.05$). This coincided with trivial or small increases in IMP_P and $IMP_{P(BM)}$ (ES = 0.05–0.43, $p < 0.05$ at 30 m). Overall, trivial to small decreases in IMP_{AP} and $IMP_{AP(BM)}$ (ES = 0.04–0.47, $p > 0.05$) were observed. With shank WR, increases to IMP_B were small at 10 m (ES = 0.38, $p > 0.05$) and moderate to large at 5 m, 20 m, and 30 m (ES = 0.85–1.27, $p < 0.05$) and increases to $IMP_{B(BM)}$ were moderate to large through all distances measured (ES = 0.67–1.97, $p < 0.05$ at 20 m and 30 m). This coincided with trivial effects to IMP_P and $IMP_{P(BM)}$ (ES = 0.01–0.16, $p > 0.05$), which taken together, resulted in decreases to IMP_{AP} and $IMP_{AP(BM)}$ that were trivial at 5 m (ES = 0.13–0.16, $p > 0.05$), small at 10 m (ES = 0.23–0.34, $p > 0.05$) and moderate at 20 m and 30 m (ES = 0.63–0.72, $p < 0.05$ only at 30 m). In the vertical direction,

IMP_V was increased by small effects (0.20–0.49, $p < 0.05$ at 10 m and 20 m) with thigh and shank WR. $IMP_{V(BM)}$ was increased by small to moderate effects (ES = 0.29–0.55, $p < 0.05$ at 20 m) with thigh WR and small to large effects (ES = 0.42–0.92, $p < 0.05$ at all distances) with shank WR.

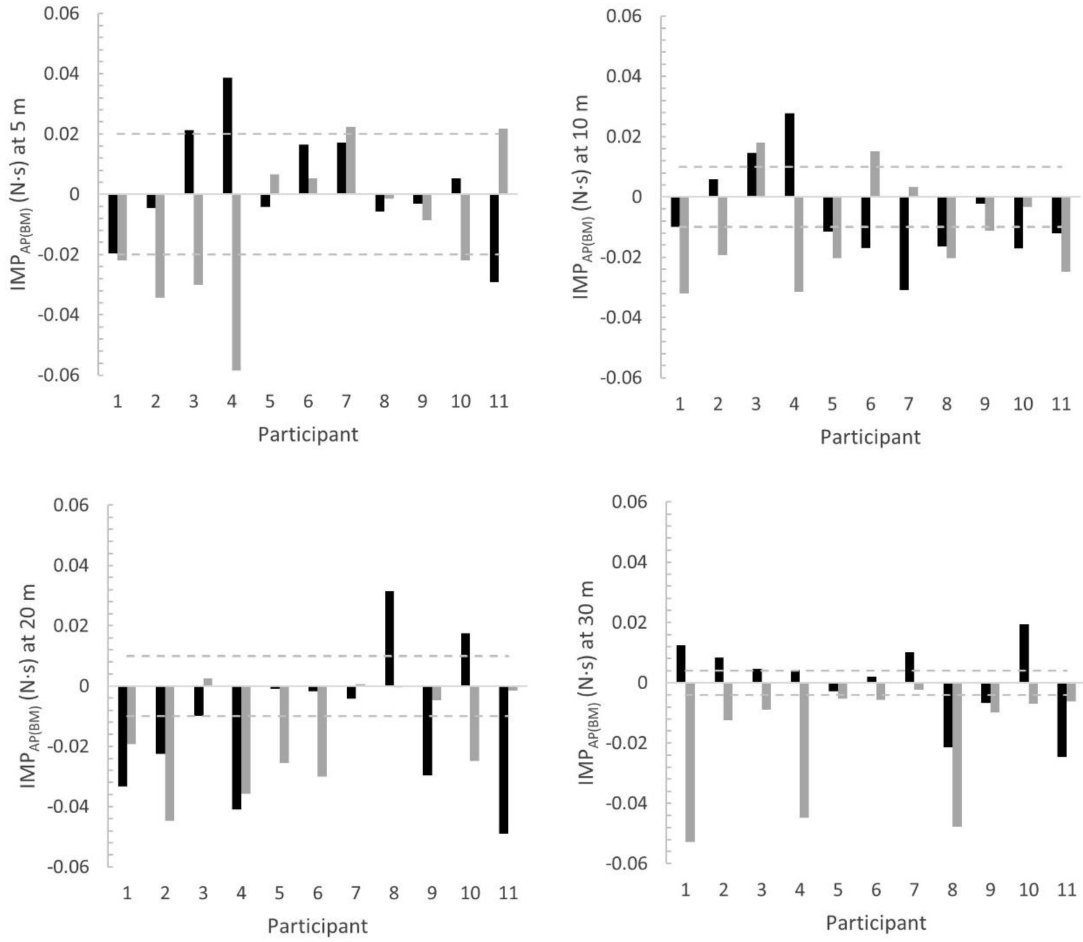
Table 7. Mean and standard deviation of impulse measures for each sprint running condition with post-hoc *p*-value and effect size statistics

	Unloaded	Thigh	Shank	Thigh - Unloaded	Shank - Unloaded	Thigh - Shank
	$\bar{x}$ (SD)	$\bar{x}$ (SD)	$\bar{x}$ (SD)	*p*-value; ES	*p*-value; ES	*p*-value; ES
Impulse (N·s)						
IMP_{AP}						
5 m	43.2 ± 6.21	43.6 ± 6.47	42.3 ± 5.93	0.40; 0.06	0.07; 0.16	0.10; 0.21
10 m	24.9 ± 2.63	24.6 ± 3.22	23.9 ± 2.93	0.50; 0.08	0.04; 0.34	0.24; 0.23
20 m	12.9 ± 1.86	12.0 ± 2.30	11.6 ± 1.64	0.14; 0.40	0.01; 0.69	0.52; 0.20
30 m	7.90 ± 1.55	7.98 ± 2.10	6.60 ± 2.05	0.79; 0.04	0.01*; 0.72	0.01*; 0.67
IMP_P						
5 m	46.6 ± 5.75	47.3 ± 6.03	46.4 ± 5.85	0.10; 0.11	0.54; 0.05	0.21; 0.15
10 m	30.6 ± 3.50	30.5 ± 3.59	30.1 ± 3.66	0.87; 0.01	0.10; 0.14	0.18; 0.13
20 m	22.8 ± 2.35	23.0 ± 2.75	22.9 ± 2.19	0.48; 0.10	0.79; 0.03	0.68; 0.07
30 m	19.3 ± 1.64	19.9 ± 1.69	19.5 ± 1.68	0.02*; 0.35	0.47; 0.08	0.05*; 0.27
IMP_B						
5 m	−3.23 ± 0.89	−3.52 ± 0.42	−4.08 ± 1.10	0.28; 0.43	0.02*; 0.85	0.11; 0.74
10 m	−4.83 ± 0.80	−5.14 ± 0.83	−5.19 ± 1.08	0.24; 0.38	0.10; 0.38	0.89; 0.06
20 m	−10.1 ± 1.14	−11.3 ± 0.96	−11.6 ± 1.16	<0.01*; 1.17	<0.01*; 1.27	0.41; 0.23
30 m	−11.4 ± 1.42	−12.0 ± 1.53	−12.9 ± 1.65	0.15; 0.35	0.01*; 0.94	0.02*; 0.59
IMP_V						
5 m	156 ± 18.5	161 ± 14.6	160 ± 18.2	0.06; 0.28	0.02; 0.23	0.85; 0.03
10 m	153 ± 18.9	156 ± 18.2	158 ± 16.1	0.03*; 0.20	0.01*; 0.34	0.25; 0.13
20 m	159 ± 17.9	164 ± 16.2	163 ± 19.1	<0.01*; 0.35	<0.01*; 0.29	0.72; 0.03
30 m	153 ± 14.0	158 ± 12.6	160 ± 16.6	0.10; 0.34	0.05*; 0.49	0.24; 0.20
Impulse relative to body mass ($m \cdot s^{-1}$)						
$IMP_{AP(BM)}$						
5 m	0.63 ± 0.08	0.63 ± 0.08	0.62 ± 0.08	0.62; 0.04	0.18; 0.13	0.25; 0.17
10 m	0.37 ± 0.05	0.37 ± 0.05	0.36 ± 0.05	0.24; 0.13	0.06; 0.23	0.53; 0.10
20 m	0.19 ± 0.03	0.17 ± 0.03	0.17 ± 0.03	0.11; 0.47	0.01; 0.63	0.67; 0.14
30 m	0.11 ± 0.02	0.12 ± 0.03	0.10 ± 0.03	0.90; 0.04	0.01*; 0.72	0.02*; 0.67
$IMP_{P(BM)}$						
5 m	0.68 ± 0.07	0.68 ± 0.07	0.68 ± 0.08	0.20; 0.10	0.92; 0.01	0.48; 0.10
10 m	0.44 ± 0.04	0.44 ± 0.04	0.44 ± 0.05	0.62; 0.05	0.20; 0.14	0.51; 0.09
20 m	0.33 ± 0.03	0.33 ± 0.03	0.33 ± 0.03	0.65; 0.07	0.54; 0.07	0.97; 0.00
30 m	0.28 ± 0.02	0.29 ± 0.02	0.28 ± 0.02	0.03*; 0.43	0.24; 0.16	0.13; 0.28
$IMP_{B(BM)}$						
5 m	−0.05 ± 0.01	−0.05 ± 0.01	−0.06 ± 0.02	0.23; 0.31	0.04; 0.67	0.23; 0.46
10 m	−0.07 ± 0.01	−0.08 ± 0.01	−0.08 ± 0.01	0.41; 0.29	0.04; 0.70	0.53; 0.36
20 m	−0.15 ± 0.01	−0.16 ± 0.01	−0.17 ± 0.01	<0.01*; 1.35	<0.01*; 1.97	0.27; 0.37
30 m	−0.17 ± 0.02	−0.17 ± 0.02	−0.19 ± 0.02	0.17; 0.34	<0.01*; 1.05	0.02*; 0.66
$IMP_{V(BM)}$						
5 m	2.26 ± 0.18	2.33 ± 0.12	2.33 ± 0.15	0.07; 0.42	0.01*; 0.42	0.84; 0.04
10 m	2.21 ± 0.18	2.26 ± 0.16	2.31 ± 0.14	0.06; 0.29	0.01*; 0.62	0.01*; 0.33
20 m	2.30 ± 0.16	2.37 ± 0.14	2.38 ± 0.17	0.01*; 0.53	<0.01*; 0.51	0.78; 0.04
30 m	2.22 ± 0.11	2.28 ± 0.11	2.33 ± 0.14	0.13; 0.55	0.04*; 0.92	0.11; 0.43

Note: IMP_{AP} = net anterior posterior impulse; IMP_P = propulsive impulse; IMP_B = braking impulse; IMP_V = vertical impulse; * = significant post-hoc comparison ($p \leq 0.05$) coinciding with a significant main test effect.

The individual responses to thigh and shank WR for $IMP_{AP(BM)}$, reported as the absolute change from the unloaded condition (i.e. WR – unloaded) are presented in Figure 7. A variety of individual responses were recorded across the distance-matched steps and between the two loading conditions. Some athletes increased $IMP_{AP(BM)}$ at one step distance and decreased at another (e.g. participant 4). Also, some athletes responded in different directions between the two loading conditions, e.g. increase in $IMP_{AP(BM)}$ with thigh WR and decrease with shank WR. Individual responses to $IMP_{P(BM)}$, $IMP_{B(BM)}$, and $IMP_{V(BM)}$ are provided as supplementary material in Appendix 1.

Figure 7. Absolute change in relative anterior-posterior impulse from the unloaded condition with thigh (black) and shank (grey) wearable resistance for each participant at each distance-matched step (5, 10, 20, and 30 m)



Note: Dashed lines indicate the smallest worthwhile change threshold (± 0.20 × unloaded condition between-subject standard deviation); IMP_{AP} = net anterior-posterior impulse.

4.4 Discussion

The effects of 2% BM lower-limb WR (attached to the thigh or shank) on sprint times, V_{max}, horizontal F-v mechanical variables, and impulse production during sprint running acceleration was quantified in this study. The main findings were: 1) increases in sprint times and reductions in maximum velocity were trivial to small when using thigh WR (0.00–1.93%) and small to moderate with shank WR (1.56–3.33%); 2) athletes maintained or significantly increased horizontal F-v mechanical variables while sprint running with WR (effect size = 0.32–1.23), except for V_0 during thigh WR and P_{max}, V_0, and RF_{max} during shank WR; 3) greater increases to braking and vertical impulses were observed with shank WR (2.72–26.3% compared to unloaded) than with thigh WR (2.17–12.1 % compared to unloaded) when considering the entire acceleration phase; and, 4) no clear trends were observed in many of the individual responses. These results support the hypothesis that the greater rotational inertia associated with the WR placed on the shank would result in greater changes to the horizontal F-v and impulse measures than the same WR load placed on the thigh.

Attaching an external load to the lower-limbs during sprint running will increase the rotational workload of the lower limbs in addition to increasing the total system mass [59]. Coaches and strength and conditioning practitioners interested in lower-limb WR training should be cognisant of the load placement with regards to the magnitude of the rotational overload desired. The same load magnitude placed further from the hip joint will increase the rotational overload (as quantified by the moment of inertia) by a function of the distance from this key axis of rotation (i.e. mass × distance^2). The impact of a load placement change is readily evident to the athlete based on sensory feedback but, also, the findings of this and previous research highlight the impact of a load placement change to athlete performance. In this study, V_{max} was significantly decreased by both thigh and shank WR but the decrease was to a greater effect with shank WR (moderate versus small). Previously, researchers have reported 1–3% BM thigh WR produced decreases in step velocity by –0.86 to –2.35% [48,60,61] but just ~0.6% BM shank WR has been shown to produce similar decreases in step velocity (–1.20% to –2.23%) [48,107]. The significant changes to velocity and sprint time measures, along with the number of participants exceeding the V_0 SWC threshold (Figure 6), highlight the consistency in athlete response to the standardised limb load prescription by using a percent of BM. It is possible that other methods could be effective to standardise WR prescriptions such as using a velocity decrement. However, from a practical standpoint, the increases to sprint times in this study were < 0.10 s on average, reinforcing the principle that lower-limb WR allows for a velocity-specific form of resistance training for sprint running [31,36]. It has also been confirmed that the rotational work at the hip joint is significantly increased with 2% BM thigh WR providing a means to increase the mechanical work of the lower-limbs specific to sprint running [59].

Investigating acute kinetic changes that occur during the use of a training method can help coaches more thoroughly understand the training stimulus induced and determine how to use the training method to generate performance improvements. In this study, the athletes were able to maintain or increase some mechanical characteristics of external horizontal force production while loaded. Most notably F_0 and $F_{0(BM)}$ levels were maintained with shank WR and increased by small effects with thigh WR. Additionally, the athletes maintained $P_{max(BM)}$ and RF_{max} levels with thigh WR while the same WR load placed on the shank resulted in significant, small decreases to $P_{max(BM)}$ and RF_{max}. It appears that the WR encouraged a physiological (i.e. internal force production) or technical (i.e. orientation of force) response that allowed the athlete to maintain external horizontal force production during initial acceleration, especially with thigh WR where seven of the 11 participants experienced increases to $F_{0(BM)}$ beyond the smallest worthwhile change threshold. However, this was not preserved over the entire 30 m sprint as evident by the slowing of sprint times, decreased V_{max} and V_0, and increased D_{RF} values with both thigh and shank WR. This suggests a given WR load (e.g. 2% BM) provides a different overload magnitude based on the movement speed of the athlete. This has also been noted previously [36] and is supported by the angular work-energy relationship. As the angular velocity of the limb increases with increasing speed, so does the angular kinetic energy of the limb, which increases the muscular work required. Coaches and strength and conditioning practitioners could choose heavier WR loads to provide a greater overload for initial acceleration during initial acceleration-specific work (e.g. block clearance drills) and lighter WR loads to provide a comparable overload during higher velocity-specific work (e.g. "flying" sprint drills) if desired.

When comparing impulse production at the distance-matched steps, IMP_B was significantly greater (large ES) with shank WR compared to the unloaded sprint running at 5 m, 20 m, and 30 m and when calculated relative to BM, $IMP_{B(BM)}$ was significantly greater (large ES) at 20 m and 30 m. Considering IMP_B and $IMP_{B(BM)}$ were only significantly increased with thigh WR at 20 m, the increases to IMP_B and $IMP_{B(BM)}$ with shank WR were primarily due to the location of the WR placement rather than the increase in system mass as the latter was consistent between the two WR conditions. For impulse to increase, there must be greater force magnitudes, a greater duration of force application (i.e. longer contact times), or some combination of the two. Considering the greater rotational overload with the shank WR placement, it is likely that the limb had greater angular momentum at the end of the forward swing phase. This would increase the challenge to stop and reverse the motion of the limb in preparation for the next ground contact. The energy of the limb at the end of the swing phase is absorbed by the work of the hip and knee joints [78]. If the greater momentum is not fully countered by the work of the hip and knee joints, the horizontal velocity of the foot at touchdown could be altered or the distance between the foot and COM at touchdown (i.e. increased touchdown distance) could be increased. Both have been suggested to be related to horizontal ground reaction forces [9,47], and thus, could result in greater horizontal impact forces, greater time spent reversing braking forces to transition to propulsion, or a combination of the two. Future studies could attempt to determine the effect of lower-limb WR on the magnitude of horizontal force across the duration of ground contact to better understand this.

Although $IMP_{B(BM)}$ is not a strong predictor of sprint acceleration velocity [47,75], more detailed analyses have revealed the importance of attenuating braking forces as acceleration progresses for improving sprint running performance [22,23,80]. Athletes that better attenuated braking forces also produced greater horizontal external power [22] and differences between sprinters and soccer players show sprinters better attenuate braking forces during the latter portion of the braking phase [23]. From these findings, it has been suggested that a component of training for sprint running should include working to improve the athlete's ability to resist and reverse braking forces [22,23]. Lower-limb WR may provide a unique training stimulus to overload $IMP_{B(BM)}$ during acceleration especially when WR placement is located on the shank.

With shank WR, IMP_V and $IMP_{V(BM)}$ were significantly increased at each of the distance-matched steps except for IMP_V at 5 m (small to large ES). With thigh WR, the only significant increases were found at 10 m (IMP_V, small ES) and 20 m (IMP_V and $IMP_{V(BM)}$, small and moderate ES, respectively). The greater rotational overload of shank WR likely increased the challenge to reposition the limb during swing and athletes may have subsequently used longer flight times to reposition the limb. To achieve longer flight times a greater vertical take-off velocity would be required and this would need to be accomplished with greater vertical impulse production during the preceding ground contact. It has been speculated that during acceleration the magnitude of $IMP_{V(BM)}$ should be only that needed to produce sufficient flight time to reposition the limb, otherwise, force production should be oriented horizontally [47]. However, considering ground contact time decreases with increasing speed [76], an athlete's ability to produce sufficient $IMP_{V(BM)}$ to maintain flight time as ground contact time decreases must come from increased vertical force production. Shank WR, in particular, appears to encourage greater $IMP_{V(BM)}$ during sprint running acceleration although this may be a consequence of how the athlete handles the load during the flight phase. It is also possible that the greater $IMP_{V(BM)}$ is a result of increased vertical impact forces. In accordance with the two-mass model of human running [17,18], the addition of mass to the shank with WR could result in greater impact forces upon ground contact. Future studies could therefore attempt to understand the underlying influence of force magnitude and ground contact time on observed changes in vertical impulse during sprint running with lower-limb WR.

This study aimed to determine the effect of thigh and shank WR on horizontal F-v and impulse measures. An important next step is to detail the change to ground reaction force time-histories to determine if the greater impulses with lower-limb WR are a result of greater ground contact times, altered time spent in braking or propulsion, increased force magnitudes at a particular part of stance or throughout the entire stance phase, or a combination of some or all of the above factors. The WR loading schemes used in this study did not equate the magnitude of rotational overload between the two placement locations. While it appears that the placement of the shank WR might uniquely affect mechanical output and impulse during sprint running over thigh WR, this cannot be fully confirmed without first equating the magnitude of the rotational overload between the two placement locations. This has been investigated with lighter WR loads during maximal velocity sprint running [48], looking only at spatiotemporal and angular kinematic measures, but this has yet to be investigated during acceleration or with rotational overload equated to the 2% BM shank WR used in this study. Finally, training studies that elucidate the longitudinal kinematic and kinetic adaptations to WR training need to be prioritised.

4.5 Conclusion

This study provided further evidence that 2% BM WR placed on the thigh or shank overloads sprint running acceleration. However, the minimal changes to sprint times (i.e. on average < 0.10 s at 30 m) highlighted the velocity-specific nature of this resistance training method. Alterations to impulse production occurred at 20 m and 30 m distances with thigh WR but were present as early as 5 m with shank WR. Although braking and vertical impulses were increased with WR, athletes were able to largely maintain propulsive and net anterior-posterior impulse levels relative to BM at the distance matched steps with external resistance. The analysis of the individual data, for the most part, reinforces the notion that athletes adapt differentially to the same loading and programming for performance change can be complex. These findings provide insight into what mechanical competencies are overloaded by lower-limb WR and may be influenced over time to produce positive speed adaptations.

Chapter 5. Waveform Analysis of Shank Loaded Wearable Resistance During Sprint Running Acceleration

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Feser EH, Neville J, Bezodis N, Macadam P, Uthoff AM, Nagahara R, Tinwala F, Cronin JB. Waveform analysis of shank loaded wearable resistance during sprint running acceleration. [published online ahead of print, 2021 Apr 18]. *J Sports Sci*. 2021;1-8. doi: 10.1080/02640414.2021.1912966.

Author contributions: Feser 82%, Neville 5%, Bezodis 3%, Macadam 2%, Uthoff 2%, Nagahara 2%, Tinwala 2%, and Cronin 2%

5.0 Prelude

In addition to some practical aspects of using shank WR over thigh WR during sprint running (e.g. ease of putting on the garment in a training setting), it was concluded from Chapter 3 and 4 that there may be potential mechanistic advantages of using shank WR. It was found that athletes were largely able to maintain joint kinematics and propulsive and net anterior-posterior impulse levels during sprint running with shank WR, even though a greater rotational overload was induced compared to that of thigh WR owing to the greater distance between the applied load and the hip joint centre. Additionally, it appears that shank WR may encourage greater vertical impulse production and directly challenge the athletes' ability to resist and reverse braking forces, both important characteristics of fast sprint running. Therefore, the focus of the research for the remainder of the thesis was on shank WR. However, the greater increases to relative braking and vertical impulse with shank WR compared with thigh WR (Chapter 4) warranted further investigation. If the greater braking and vertical impulse seen with shank WR are a result of large horizontal or vertical forces during impact, this could raise concern for an increased risk of repetitive stress injuries, which in turn could have implications for prescribing shank WR training. Quantifying impulse in Chapter 4 only provides a macroscopic measure of the force production characteristics for each step of sprint running, as it is not possible to determine the underlying cause of greater impulse. As impulse is the product of force and the time duration of force production, greater impulse values could be a result of greater contact times, greater force magnitudes at a particular part of stance or throughout the entire stance phase, or some combination thereof. A force waveform analysis provides the necessary detail to determine if the ground reaction forces produced during unloaded and shank WR sprint running differ across ground contact. Specifically, this analysis method allows for identification of differences between two force waveforms throughout ground contact, which is not available via discrete variable analyses such as comparing mean or peak values. Therefore, the purpose of this chapter was to compare the force waveforms and contact times between unloaded and 2% BM shank WR sprint running. This provided the detailed information necessary to understand the previously observed changes in impulse and to determine if horizontal or vertical forces were significantly increased with shank WR at ground impact.

5.1 Introduction

Wearable resistance (WR) can be used for high-velocity resistance training of sport-specific movement patterns [31,36,54,56]. The load magnitude used for limb WR training is often very low (e.g. ≤ 3% of BM), which allows the resistance training to take place at or near typical movement speeds.[36] When WR is attached to the limb, the overload can be modulated by moving the load proximal-distal from the axis of rotation, thus increasing the rotational inertia of the limb. The loads can be positioned to increase the mechanical work of particular joints and, therefore, target specific musculature [59,66]. For sprint running, WR can be positioned on the shank to overload the muscles spanning the hip and knee joints. This provides a specific and targeted overload to the movements involved in sprint running [59,66], making shank WR training of great interest for improving sprint running speed. However, practitioners should be cognisant of how the athlete responds to rotational inertial changes consequent to a specific WR placement and magnitude to ensure the resulting overload adheres to the training stimulus intended.

Shank WR has been shown to increase vertical and horizontal braking impulse during sprint running acceleration [37]. Specifically, 2% BM shank WR resulted in small to large increases in relative vertical impulse (3.05–5.23%, ES = 0.42–0.92, p <0.05) and moderate to large increases in relative horizontal braking impulse (9.63–20.8%, ES = 0.67–1.97, p <0.05) compared to unloaded sprint running for steps at 5 m, 10 m, 20 m, and 30 m [37]. These findings led to the suggestion that shank WR provides a unique stimulus which may be used to improve an athlete's ability to resist and reverse horizontal braking forces during acceleration [37] which is thought to be a distinguishing characteristic of faster sprint running [22,23].

It is possible however, that greater horizontal and/or vertical impact forces occur with the addition of mass to the shank. In the vertical direction, a contributing factor to the forces at impact corresponds to the deceleration of the foot and shank [18,19]. The addition of mass to the shank could have a direct effect on the vertical impact forces by imposing greater deceleration needs, especially at faster speeds when the sprinter is inevitably in a more upright position following in accordance with the two-mass model of human running [17,18]. In the horizontal direction, the added shank mass could result in greater forward velocity (relative to the ground) of the foot at touchdown especially if the sprinter cannot fully counter the increased forward momentum of the limb at the end of the swing phase. The horizontal velocity of the foot at touchdown has been suggested to be related to the horizontal braking forces during sprint running [47]. Thus, if the forward velocity of the foot at touchdown is increased with shank WR, the athlete could experience greater impact forces in the horizontal direction. If sprint running with shank WR results in higher impact forces, there could be concern for risk of repetitive stress injuries. While repetitive stress injury rates may not be as high in sprinters compared to distance runners, sprinters have been reported to sustain bone stress injuries during training[81] and ground reaction force magnitude and rate have been considered one of the biomechanical risk factors of bone stress injury [103]. Practitioners would need to exercise caution when prescribing shank WR training to ensure an accumulation of training volume that could be injurious does not occur.

The research available to date does not provide the necessary details to determine if the higher vertical and horizontal braking impulse values seen with shank WR are a result of longer contact times, altered proportions of time spent in braking and propulsion, greater force magnitudes at a particular part of stance or throughout the entire stance phase, or some combination thereof. A more detailed investigation into the ground reaction forces produced when sprint running with shank WR is warranted to better understand the underlying cause(s) for increased horizontal braking and vertical impulse. A force waveform analysis and contact time comparison provides the further detail needed to better understand impulse production during each step. Specifically, a systematic analysis of the force waveforms enables a deeper understanding of ground reaction force production than that available with a discrete variable analysis. Therefore, the purpose of this study was to compare the contact times and force waveforms between sprint running with no load and 2% BM shank WR. Given increased contact times are commonly reported with lower-limb WR [36] but in this study a relatively light loading scheme was employed, it was hypothesised that shank WR would result in longer contact times but not greater horizontal or vertical impact forces.

5.2 Methods

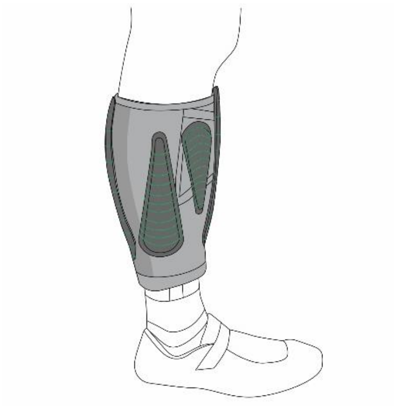
5.2.1 Participants

Fifteen male university-level sprint specialists volunteered to participate in this study (age = 21.1 ± 2.22 years, mass = 67.2 ± 4.58 kg, height = 1.74 ± 0.05 m). The athletes had an average 100 m best time of 11.44 ± 0.42 s and training experience of 9.33 ± 2.74 years. Study procedures were approved by the host University Institutional Review Board and written informed consent was obtained before study participation.

5.2.2 Experimental Procedures

Athletes reported to an indoor training facility and began the intervention by completing a self-selected warm-up which included dynamic stretching, running drills, and a series of submaximal effort sprints (i.e. 50%, 75%, and 90% of maximal effort). Following the warm-up, each athlete completed four maximal effort 50 m sprint trials from starting blocks wearing their own spiked running shoes. The sprint trials consisted of two repetitions with WR attached to the shank and two repetitions unloaded (no WR) completed in a randomised order. For all sprint trials, the athletes wore Lila™ Exogen™ (Sportboleh Sdh Bhd, Kuala Lumpur, Malaysia) calf sleeves which allowed for Velcro backed "micro-loads" to be attached to the garment for the loaded trials. The loads were attached in line with the long axis of the shank and totalled in magnitude 2% BM (i.e. 1% BM attached to each limb) per Feser et al. [37] (Figure 8). The exact loading magnitudes ranged from 1.90–2.11% due to the loading increments available (100, 200, and 300 g). The sprint trials were completed on an indoor track surface (Hasegawa Sports Facilities Co., Hasegawa, Japan) which housed a series of in-ground force platforms (TF-90100, TF-3055, TF-32120, Tec Gihan, Uji, Japan) that covered a total distance of 52 m. This allowed for ground reaction force measurement at 1000 Hz across the entire acceleration phase (defined here as following block clearance to 30 m). Each sprint start was signalled with an electronic starting gun (Digi Pistol, Molten, Hiroshima, Japan).

Figure 8. Example wearable resistance load placement



5.2.3 Data Analysis

The ground reaction force data were filtered with a fourth-order Butterworth low-pass digital filter, cut-off frequency 50 Hz. Movement onset was defined as the time point where the resultant ground reaction force increased and remained above two standard deviations greater than the mean value during the initial stationary period. Individual steps were identified from the filtered ground reaction force data by detecting the touchdown and take-off with a 20 N vertical ground reaction force threshold. The horizontal centre of mass velocity was calculated from the initial movement to maximal velocity [22] by determining the instantaneous horizontal velocity throughout the entire sprint from the anterior-posterior impulse and estimated aerodynamic drag [93]. From the horizontal centre of mass velocity-time data, a distance-time relationship was derived for each sprint trial. This was done so the steps at 5 m, 10 m, 20 m, and 30 m could be extracted per Feser et al. [37] and used for analysis. The step number used for each experimental condition along with the corresponding time, distance, velocity at toe-off, and percent of maximal toe-off velocity are reported in Table 8.

5.2.4 Statistical Analysis

A series of paired-samples t-tests were used to test for differences in contact time between the shank and unloaded conditions at the distance-matched steps of 5 m, 10 m, 20 m, and 30 m. No outliers, were found as defined by a value greater than 3 box-lengths from the edge of a boxplot. The differences between the shank loaded and unloaded contact time measures were normally distributed, as assessed by Shapiro-Wilk's test ($p > 0.05$) and Normal Q-Q Plot visual inspection. Analyses were performed using SPSS Statistics (Version 25, IBM, Armonk, NY, USA). Significance was set at $p \leq 0.05$. ES statistics (Cohen's *d*) were calculated as the mean of the within-subjects difference scores divided by the average standard deviation of the two conditions [53] and described as trivial (<0.20), small (0.20), moderate (0.50) and large (0.80) [21]. Individual response to the shank WR was classified as an increase or decrease if the individual change from the unloaded condition was > ± 0.2 × unloaded between-subject standard deviation (i.e. smallest worthwhile change) [21].

The vertical and anterior-posterior components of the ground reaction force waveforms at each of the distance-matched steps underwent a curve analysis using Statistical Parametric Mapping [85] (SPM, version 0.4, http://www.spm1d.org/) in MATLAB (MATLAB R2019b, The MathWorks, Inc., Natick, Massachusetts, USA). This method allowed for identification of differences throughout ground contact rather than focussing just on discrete events. The force waveforms were temporally normalised to 0% to 100% of ground contact (i.e. each step was time normalised to 1000 data points) using an inbuilt cubic spline function. The time normalised waveforms for each experimental condition were then averaged to represent athlete performance at each distance-matched step. As part of the statistical parametric mapping analysis process, a paired-samples t-test was used to test for differences between the shank loaded and unloaded conditions in anterior-posterior force and vertical force (both body weight normalised) at the distance-matched steps of 5 m, 10 m, 20 m, and 30 m in accordance with previous research [37]. Significance was set at $p \leq 0.05$.

Table 8. Time, distance, velocity, percent of maximal velocity (mean ± SD) and the step number used at each distance of interest for the unloaded and shank conditions' distance-matched steps

	Step (#)		Time at toe-off (s)	Distance at toe-off (m)	Velocity at toe-off (m·s^{-1})	Percent of maximal velocity at toe-off (%)
5 m	3 (n = 2), 4 (n = 12), 5 (n = 1)	**U**	1.29 ± 0.08	5.07 ± 0.46	6.49 ± 0.28	70.0 ± 2.45
		S	1.30 ± 0.07	5.02 ± 0.35	6.38 ± 0.25	71.1 ± 1.99
10 m	6 (n = 2), 7 (n = 11), 8 (n = 2)	**U**	1.98 ± 0.09	9.90 ± 0.53	7.75 ± 0.31	83.5 ± 1.55
		S	2.01 ± 0.08	9.87 ± 0.35	7.60 ± 0.30	84.8 ± 1.45
20 m	11 (n = 2), 12 (n = 6), 13 (n = 5), 14 (n = 2)	**U**	3.20 ± 0.15	20.0 ± 0.72	8.81 ± 0.38	95.0 ± 1.02
		S	3.26 ± 0.15	19.9 ± 0.57	8.60 ± 0.36	95.9 ± 0.94
30 m	16 (n = 2), 17 (n = 5), 18 (n = 5), 19 (n = 3)	**U**	4.36 ± 0.20	30.3 ± 0.84	9.19 ± 0.41	99.0 ± 0.44
		S	4.44 ± 0.18	30.2 ± 0.42	8.92 ± 0.41	99.4 ± 0.37

Note: U = unloaded condition, S = shank loaded condition.

5.3 Results

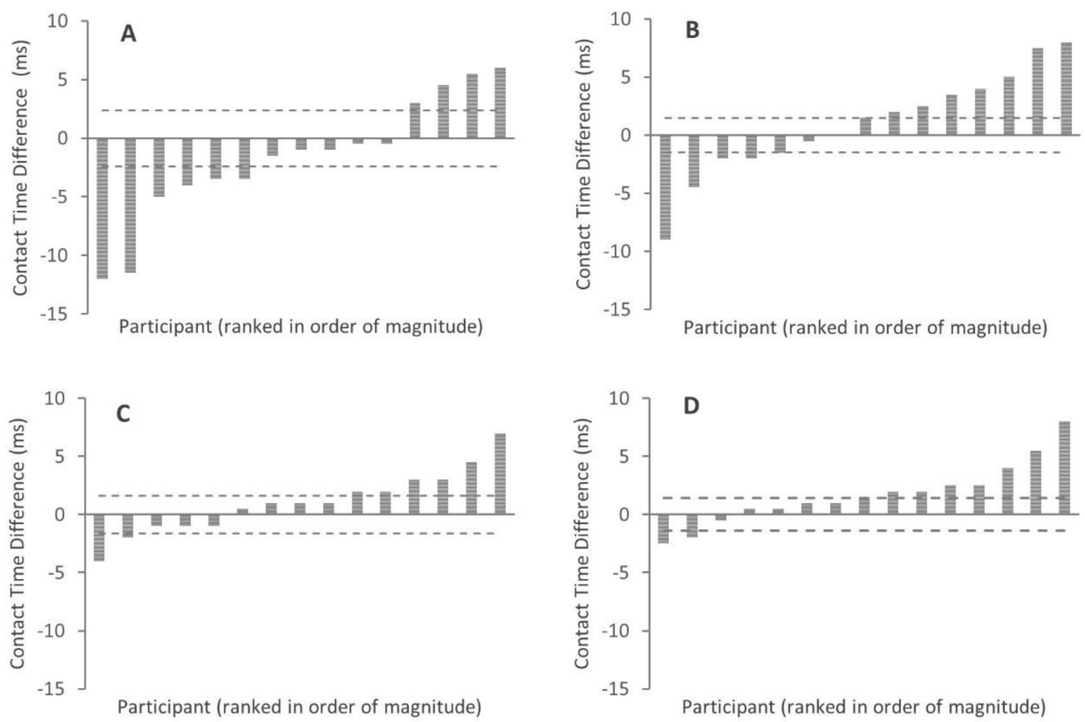
Sprint running with shank WR resulted in 30 m sprint times that were 1.80% slower than unloaded sprint running. Shank WR produced trivial changes to contact times at 5 m, 10 m, and 20 m (ES < 0.20, $p > 0.05$) and a small, significant increase to contact time at 30 m by 1.94% (ES = 0.25, $p = 0.03$) (Table 9). Individual change in contact time between the unloaded and shank loaded conditions (i.e. shank loaded contact time – unloaded contact time) at each distance-matched step are shown in Figure 9. The majority of participants (6/10) that experienced a change in contact time at 5 m demonstrated a reduction in contact time. The majority of participants that experienced a change in contact time at 10 m, 20 m, and 30 m demonstrated an increase in contact time (7/11, 6/8, and 8/10, respectively).

Table 9. Contact time mean and standard deviation measures for each sprint running condition with paired-samples t-test p-value and Cohen's *d* effect size statistics

	Unloaded	**Shank loaded**	**Shank loaded - Unloaded**
	$\bar{x}$ (SD)	$\bar{x}$ (SD)	*p*-value; ES
5 m CT (ms)	143 ± 12.0	141 ± 13.9	0.18; 0.15
10 m CT (ms)	125 ± 7.58	126 ± 8.87	0.42; 0.12
20 m CT (ms)	110 ± 8.01	111 ± 8.60	0.15; 0.13
30 m CT (ms)	103 ± 7.11	105 ± 6.67	0.03*; 0.25

Note: CT = contact time; * = significant difference between unloaded and shank loaded; ES = effect size.

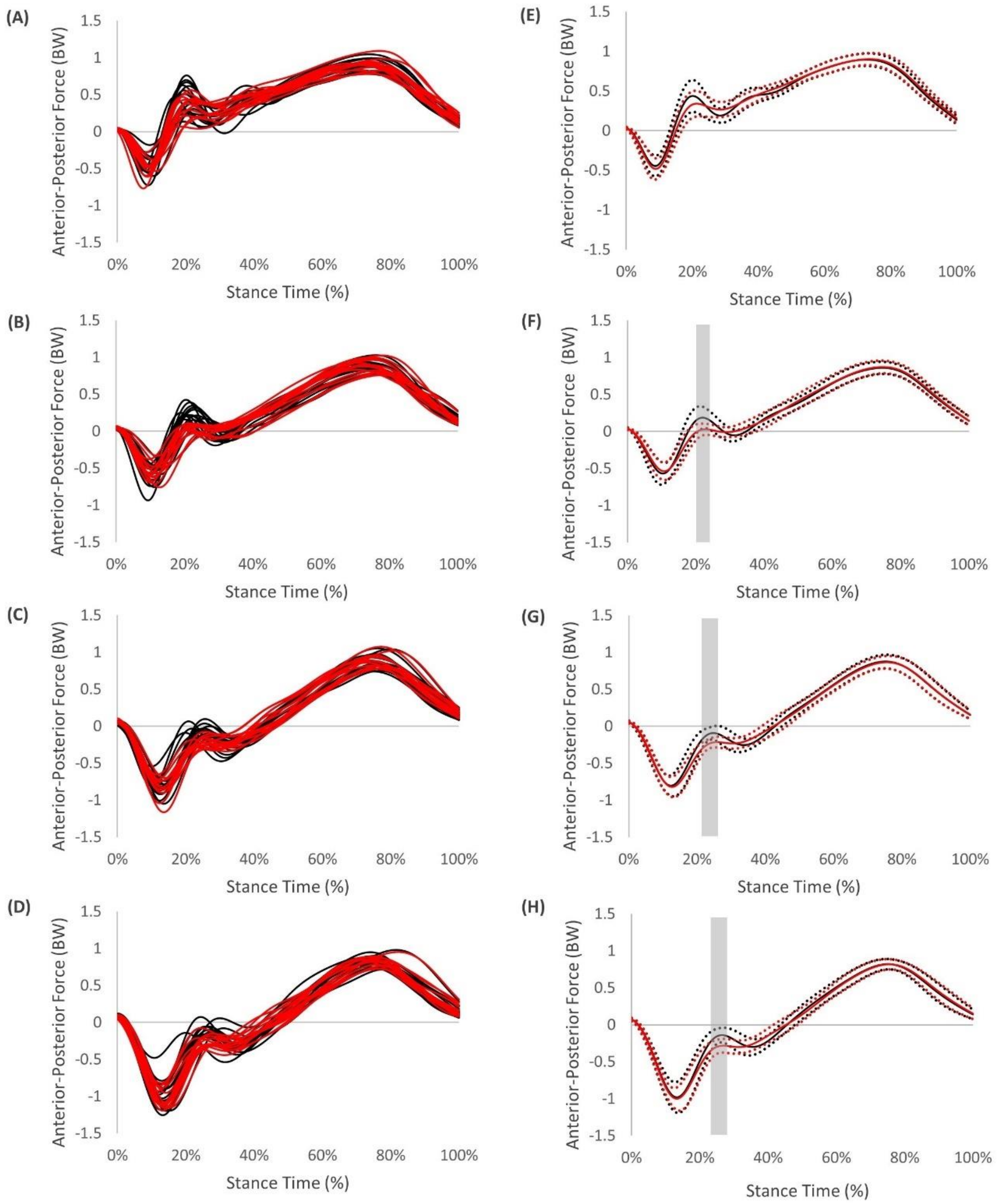
Figure 9. Individual change in contact time between the unloaded and shank loaded conditions for each participant ($n = 15$) at each distance-matched step



Note: A = 5 m, B = 10 m, C = 20 m, D = 30 m. The values are ranked in order of magnitude. A positive value indicates a higher contact time in the shank loaded condition. Dashed lines indicate the smallest worthwhile change threshold (± 0.20 × unloaded condition between-subject standard deviation).

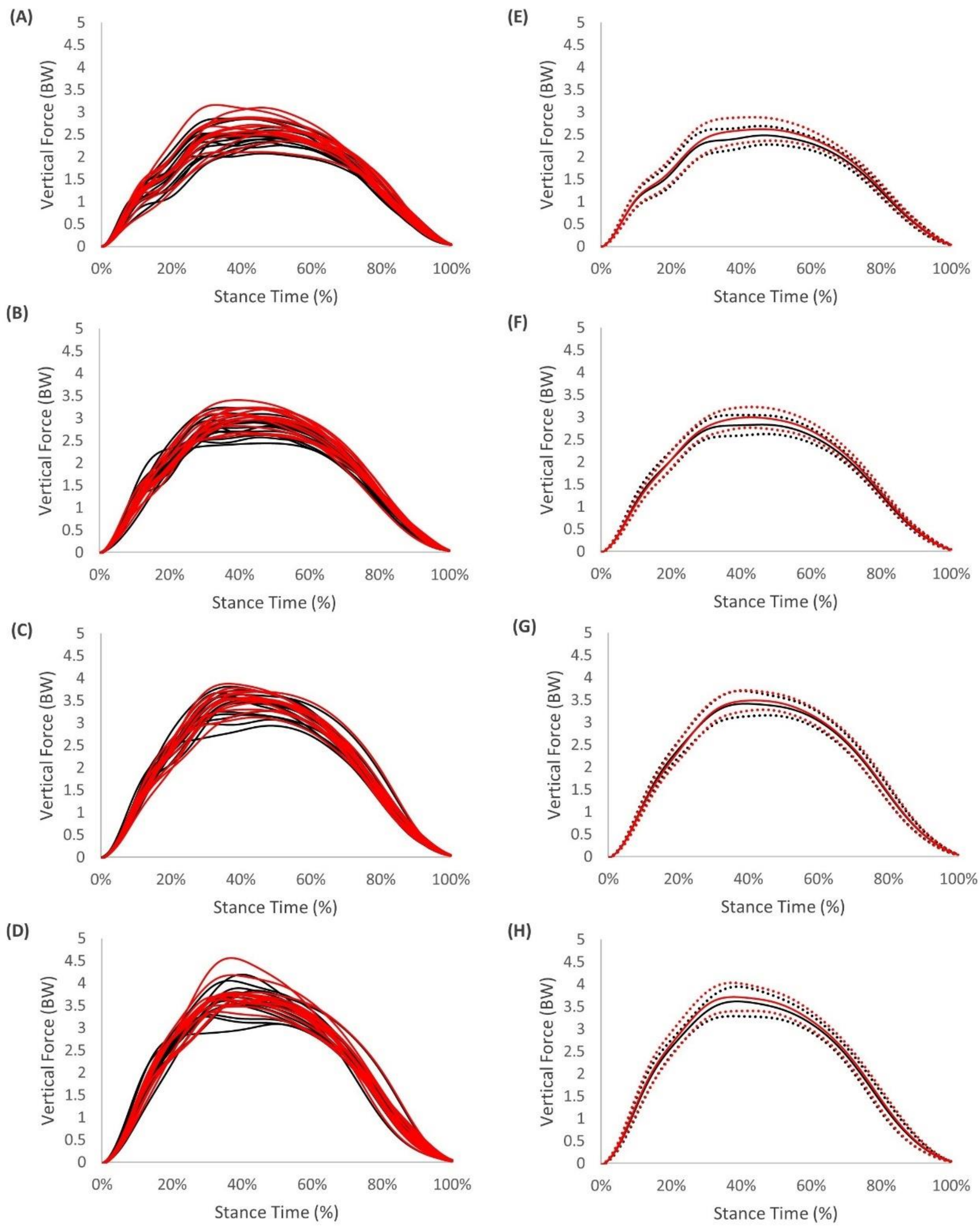
There were significant differences in the anterior-posterior force waveforms during the early-mid (i.e. 20–30%) part of stance for the steps analysed from 10 m onwards. Specifically, propulsive force was significantly decreased when sprint running with shank WR from 20.8–24.2% of ground contact for the step at 10 m. Horizontal braking force was significantly increased when sprint running with shank WR from 21.4–26.0% and 23.9–28.3% of ground contact for the steps at 20 m and 30 m, respectively (Figure 10). There were no significant differences in vertical force between unloaded and shank WR sprint running (Figure 11).

Figure 10. Anterior-posterior force waveforms (force units standardised to body weight) for the step at 5 m, 10 m, 20 m, and 30 m during unloaded (black) and shank loaded (red) sprint running



Note: The left column shows average force waveforms for each participant at 5 m (A), 10 m (B), 20 m (C), and 30 m (D). The right column shows mean (solid line) and standard deviation (dotted line) for each condition at 5 m (E), 10 m (F), 20 m (G), and 30 m (H). The gray bar indicates the sections of the waveform where the SPM curve exceeded the critical threshold representing a statistically significant difference between the two conditions ($p < 0.05$).

Figure 11. Vertical force waveforms (force units standardised to body weight) for the step at 5 m, 10 m, 20 m, and 30 m during unloaded (black) and shank loaded (red) sprint running



Note: The left column shows average force waveforms for each participant at 5 m (A), 10 m (B), 20 m (C), and 30 m (D). The right column shows mean (solid line) and standard deviation (dotted line) for each condition at 5 m (E), 10 m (F), 20 m (G), and 30 m (H). No statistically significant differences were present between the two conditions at any of the step distances ($p > 0.05$).

5.4 Discussion

Understanding the mechanical effects of shank loaded WR is important to determine its potential as a training tool, but also to determine if the user needs to be aware of the possibility of increased force magnitudes which may be associated with injury risk. This study, therefore, compared the force waveforms and contact times between sprint running with no load and 2% BM shank WR, for the distance-matched steps at 5 m, 10 m, 20 m, and 30 m. The hypothesis that sprint running with shank WR would result in longer contact times but not greater horizontal or vertical impact forces was partially supported. The main findings were: 1) group-mean changes to contact time with shank WR were non-significant and trivial until 30 m where contact time was significantly increased by 1.94% (ES = 0.25); and, 2) significant differences in ground reaction force between unloaded and shank WR were limited to the anterior-posterior direction and occurred between 20.8–28.3% of ground contact, around the period of transition from braking to propulsion, for the distance-matched steps at 10 m, 20 m, and 30 m. Therefore, sprint running with 2% BM shank WR does not result in greater horizontal or vertical forces during the impact portion of ground contact beyond that seen with unloaded sprint running.

The WR used in this study did not significantly alter contact times until the distance-matched step at 30 m, in which contact time was increased by 1.94% (ES = 0.25). The individual changes in contact time (Figure 9) show a larger proportion of the athletes increasing contact time at greater movement velocities. Thus, it appears changes in contact time are sensitive to movement velocity when sprint running with 2% BM shank WR. The effect of shank WR on contact times during maximal velocity sprint running has been previously investigated. Researchers reported increases to contact time with ~0.60% BM shank WR by 0.88% ($p > 0.05$) [48] and 1.1% BM shank WR by 10.0% ($p < 0.01$) [107]. Although the athletes in the current study were close to maximal velocity speeds for the step at 30 m (i.e. 99.4% of maximal velocity, Table 8), the change in contact time was much less than that reported in Zhang et al. [107] who reported a 0.01 s (10%) increase with 1.1% BM shank WR (contact time = 0.01 s unloaded; 0.11 s loaded). However, it should be noted that Zhang et al. [107] reported contact time to only the hundredths place (rather than thousandths) which possibly has removed the precision needed to accurately compare their results to the findings in this study. It is likely the small, significant increase in contact time at 30 m with shank WR in this study contributes to the greater horizontal braking and vertical impulse values reported previously by researchers who used the same loading scheme [37]. Otherwise, the greater impulse values at steps 5, 10, and 20 m also reported previously with shank WR [37] must primarily come from greater magnitudes of force production across the stance phase as trivial changes to contact times were measured for the steps at these distances in this study.

The relationship between anterior-posterior force production and performance has been shown to differ throughout the stages of acceleration. During the earlier stages of acceleration (i.e. the first 11 steps), the positive relationship between anterior-posterior force production and sprint performance occurred during the propulsive phase, placing importance on concentric force production for these steps (e.g. 58–92% of ground contact at step two) [22]. In the later stages of acceleration, the positive relationship with performance occurred during the second part of the braking phase and the transition in to propulsion, emphasising the importance of being able to attenuate braking forces for improving sprint performance during these steps (e.g. 19–25%, 28–35%, and 38–64% of ground contact at step nineteen) [22]. In this study, with shank WR, significantly lower propulsive forces were found at 10 m from 20.8–24.2% of ground contact. At 20 and 30 m, representing the later stages of acceleration, significantly greater braking forces were found at a similar relative time within ground contact (21.4–26.0% and 23.9–28.3%, respectively). Thus, it appears 2% shank WR provides a direct overload to anterior-posterior force production during the early-mid part of stance around the time where the ground reaction force vector transitions between braking and propulsion, and that this appears to closely align with the features of the ground reaction forces that align with performance as the athlete travels from 10 m onwards. Considering the increase to braking force magnitudes and duration during the later parts of acceleration, it is possible that shank WR directly challenges the athlete to maintain their lower-limb stiffness resulting in the athletes experiencing greater braking forces before they can transition to propulsion. This may potentially serve as a mechanism for shank WR to improve sprint acceleration performance by enabling athletes to better attenuate braking forces following training exposure. Whilst the significant effects of shank WR on anterior-posterior forces occurred at a very similar part of the step cycle to where the magnitudes of the anterior-posterior force are known to relate to performance [22], it should be noted that these effects only occurred for ~5% of the stance phase and it remains unknown if this overload would be sufficient as a training stimulus. Future longitudinal studies could investigate if this overload would be sufficient as a training stimulus.

The waveform analysis revealed no difference ($p > 0.05$) in vertical force production between the shank loaded and unloaded sprint trials across the ground contact of each of the distance-matched steps. It is possible the athletes altered end-swing phase or touchdown mechanics to prevent substantial increases in vertical impact forces. The initial rising edge of the vertical force waveform at impact is influenced by three factors during upright sprint running; mass, vertical touchdown velocity, and deceleration time of the shank [18]. Athletes can alter two of the three variables (velocity and deceleration time) when sprint running with shank WR to limit an increase in vertical impact force. The findings here suggest these athletes were able to maintain touchdown kinetics with 2% BM shank WR to not incur large vertical impact forces and likely did so by altering vertical touchdown velocity and/or deceleration time of the shank. Visual inspection of the entire force waveforms shows slightly greater forces at midstance with shank WR which, although non-significant, are possibly a function of the greater system mass. It has been hypothesized that greater vertical forces than those during unloaded sprint running are needed to produce a greater vertical take-off velocity and, thus, greater flight times [37]. The greater flight times are thought to be needed to allow for more time to reposition the limb during swing in preparation of the next ground contact due to the constraint of increased rotational inertia. The athletes in this study were able to perform sprint running acceleration with the 2% BM shank WR without a need to significantly increase vertical force production across the stance phase. Thus, it is possible that the addition of 2% BM shank WR does not necessitate greater flight times to allow for limb repositioning.

This study was the first to investigate ground reaction force waveforms over the entire stance phase during sprint running with WR. It was found that the only significant differences between the loaded and unloaded force waveforms occurred the anterior-posterior direction during the period of transition from braking to propulsion. Future studies could consider investigating the stance by sub-phases, including direction- or feature-specific waveform analyses and contact time comparisons. A possible limitation to the findings of this study includes any influence of acute performance effects that could occur from the use of shank WR. The acute performance effects of lower-limb WR on sprint running performance have only been investigated using a combined thigh and shank WR loading scheme (1-5% BM) [95,96]. No significant changes to sprint running times were reported in these studies. However, Simperingham et al. [96] reported substantial changes (i.e. greater than two standard deviations from the baseline mean) in a single-subject analysis for the start and acceleration phase contact times (2.1-2.9%) following 40 m sprints with 1%, 3%, and 5% BM WR. Therefore, in effort to minimize any influence of potential acute performance effects for measures in this study, the athletes were provided five to ten minutes of passive rest between sprint trials and the experimental conditions were randomised.

Lower-limb WR can be used to provide a specific and targeted overload to the muscles involved in sprint running. This has made lower-limb WR training of great interest for improving sprint running speed. To-date, only a small variety of load placements and magnitudes have been investigated [36]. However, it is unknown how different load magnitudes and placements may alter ground reaction force production across the stance phase compared to the loading scheme used in this study. Practitioners should still be watchful when using different lower-limb WR schemes for any negative individual responses that may occur, especially when using loading schemes that induce greater rotational inertial changes to that studied here. This will help to ensure the appropriateness of the WR training with respect to desired training outcomes and limit the potentially injurious impact forces.

5.5 Conclusions

This study builds upon the current WR research and identifies specific kinetic effects which may render shank WR as a potentially effective training tool for sprint acceleration performance. Sprint running with 2% shank WR produced a small, significant increase to contact time at 30 m by 1.94% (ES = 0.25, $p = 0.03$). Significant differences in the anterior-posterior component of the ground reaction force between unloaded and shank WR occurred between 20–30% of ground contact at 10 m, 20 m, and 30 m. The overload provided to anterior-posterior force production coincided closely with the performance demands at these stages within acceleration. In addition, this study assists practitioners in determining if caution needs to be exercised when prescribing shank WR to reduce injury risk. The results of this study do not indicate that greater horizontal braking or vertical forces occur during the impact portion of ground contact when sprint running with 2% BM shank WR up to 30 m. Therefore, practitioners can prescribe shank WR training with loads ≤ 2% BM for sprint running training matching the speeds and distances used in this study with little concern such loading will cause injury.

Chapter 6. Wearable Resistance Sprint Running is Superior to Training with No Load for Retaining Performance in Pre-Season Training

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Author contribution: Feser 82%, Bayne 7%, Loubser 7%, Bezodis 2%, Cronin 2%

6.0 Prelude

In Chapter 2, it was noted that the research on longitudinal outcomes of lower-limb WR training for sprint running was limited with only one study completed to date. The application of the study findings to an athlete population is difficult as the training status of the participants was not disclosed, no information regarding the acceleration phase of sprint running was reported, and the rotational overload used (5% BM placed on the ankle) is not respective of that used with athletes. Given the economic viability and convenience of shank WR over thigh WR (the compression calf sleeves were more cost efficient than the compression shorts and are easier to put on and take off at the practice field), shank WR presented itself as the most practical option for lower-limb WR training in a team sport setting. The confirmation of mechanistic appropriateness in Chapters 3 and 4 provided further rationale to use shank WR as an intervention for sprint running. Therefore, the purpose of this chapter was to determine the effects of a lower-limb WR training intervention presented within the context of a pre-season training programme for well-trained rugby athletes. A 1% BM shank WR load was chosen for this study as it matched the load magnitude and placement commonly used by the coaching staff that advised on this research, which provided reassurance to and ensured buy-in of the coaching staff directly involved in this study. Additionally, with the knowledge from Chapter 5, where it was found that a shank WR placement of up to 2% BM could be used without resulting in large impact forces, the 1% BM was further deemed appropriate for longitudinal training exposure.

6.1 Introduction

Lower-limb WR training involves attaching an external load, as little as 0.5% BM, onto the athlete's thigh or calf allowing them to perform sport specific movement tasks under resistance. The load can be positioned to directly overload joints, and therefore muscles, of interest for the given movement task. This makes lower-limb WR training particularly applicable for sprint running training. The athlete can train with light resistance at high movement velocities with the overload applied below the hip and/or knee joints to facilitate more specific overload than that possible with traditional resistance training equipment (i.e. free weights and resistance training machines). Additionally, lower-limb WR training is different to traditional resistance training or the attachment of loads to the upper body, as the load also provides a rotational overload. Given these factors, it would seem that lower-limb WR training offers better training specificity and is therefore more likely to optimise the transference of any strength and metabolic improvements to the movement task of interest, e.g. sprint running [25].

Results from acute investigations have shown promise that lower-limb WR training provides an appropriate overload for sprint running training [36]. Specifically, contact time and step frequency are significantly overloaded (increased and decreased, respectively) during the acceleration and maximal velocity phases of sprint running [95,55]. This occurs with no significant coinciding change to step length or flight time. These findings suggest that lower-limb WR can be used to selectively overload particular aspects of sprint running [36]. Overloading step frequency especially may be an ideal training strategy for well-trained sprinters as it has been suggested that training at this level should target enhancing step frequency [43]. Similarly, as coaches identify performance detriments for their athletes, they may choose lower-limb WR to cue and stimulate changes in step frequency whilst other overload methods may provide different training benefits [56,61]. It is not surprising that reported acute changes in step frequency with lower-limb WR come with a change to contact time due to the greater system mass that must be accelerated in every ground contact. The lack of change to step length could indicate that spatial joint kinematics are largely unchanged when using the loading schemes investigated to-date.

Researchers have also reported significant acute changes in the horizontal force profiles of the athlete when performing sprint acceleration with WR. Significant changes in the relative F-v profile have been found with 3% BM lower-limb WR, reflecting more force dominant profiles, compared to an unloaded condition in amateur to semi-professional male rugby athletes [55,97]. These significant acute profile changes of ~10.0% resulted from a significant reduction in theoretical maximal velocity (-3.57% to -6.49%) and concurrent non-significant increase in theoretical maximal horizontal force (5.08%-6.25%) [55,97]. These findings indicate that as little as 3% BM lower-limb WR provides a sufficient overload to velocity production during acute use. Considering theoretical maximal velocity production has been shown to be positively correlated to sprint running performance [72], lower-limb WR training may have the potential to elicit improved sprint performance over time due to alterations in the mechanical sprint profile. However, the chronic adaptation to these acute changes has not been documented.

Research on longitudinal outcomes of lower-limb WRT for sprint running is limited, with only one study completed to date. Researchers found that six-weeks of sprint running with 5% BM ankle WR produced a significant increase in stride length (5.32%) and a significant decrease in stride frequency (-5.60%) with no changes to maximal running speed in University physical education students [84]. Although increases in step length have been shown to occur concurrently to increases in running speed over time and are believed important for maximal sprint running [79], the accompanying decrease in stride frequency negated any possible positive training effect on maximal sprint speed [84]. Ultimately, it is challenging to apply these findings to an athlete population as the training status or history of the participants used was not disclosed [84]. In summary, there is a lack of research-based evidence detailing how an athlete population might respond to lower-limb WR training for sprint running.

Given this paucity of research investigating the longitudinal effects of sprint training with lower-limb WR in athletes, it is of value to determine the performance adaptations that occur as an effect of lower-limb WR training. This is pre-requisite to understanding how the body responds to control the limb load and how this can be manipulated for performance improvements. Therefore, the purpose of this study was to determine the effects of a six-week lower-limb WR training intervention on sprint running time, velocity, and horizontal force-velocity mechanical variables in well-trained rugby athletes. We hypothesised that the WR training would decrease sprint running time, increase velocity, and positively influence the horizontal force-velocity mechanical variables.

6.2 Methods

Thirty-two athletes volunteered to participate in this study and were all members of the same collegiate/semi-professional rugby training squad. Inclusion criteria required athletes to have a minimum of one year of resistance training experience, be currently training, and trained as a field-based sport athlete. Athletes were excluded if they were under the age of 16, had a current or previous lower extremity injury that may be further aggravated by participating in the training, or did not pass the Physical Activity Readiness Questionnaire. All study procedures were approved by the host University Institutional Review Board.

6.2.1 Performance Testing

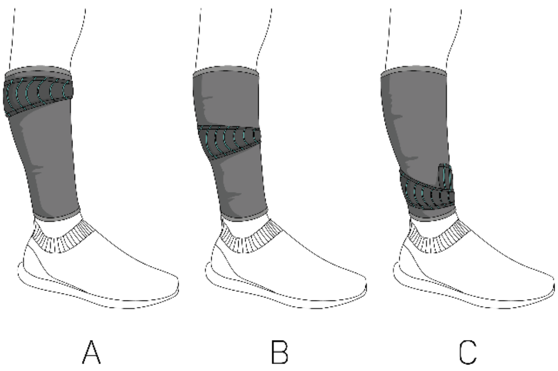
Athletes reported to an indoor fieldhouse on two occasions to complete pre- and post-intervention performance testing. Each testing session started with a warm-up protocol consistent to the athletes' typical practice session preparation. Following this, each athlete completed three maximal effort 30 m sprints, separated by a minimum of five minutes of rest.

Each sprint was performed from a two-point, split stance start position, and was initiated by the athlete when they felt ready. A radar device (Stalker ATS II, Applied Concepts, Dallas, TX, USA) was used to measure athlete velocity at 47 Hz. The radar was positioned 5 m directly behind the starting position and at a vertical height of 1 m to approximately align with the participant's centre of mass [55]. STATS software (Version 5.0.2.1, Stalker ATS II, Applied Concepts, Dallas, TX, USA) was used to collect all data.

6.2.2 Training Intervention

The sprint training occurred in tandem with a pre-season training block (which also included rugby skill and maximal aerobic speed sessions) in which the athletes reported to two dedicated sprint training sessions a week. The athletes were match-pair randomised into the WR and control groups using the pre-intervention 30 m sprint times (control group n = 15, age = 24.0 ± 2.88 years, mass = 100.8 ± 28.6 kg, stature = 179.9 ± 5.32 cm, baseline sprint time = 4.27 ± 0.22 and WR group n = 17 , 22.5 ± 2.65 years, 97.4 ± 13.1 kg, 182.6 ± 7.52 cm, baseline sprint times 4.26 ± 0.14 s). The WR group completed all sprint training sessions with 1% BM load attached to the shank with a specialised compression garment (Lila™ Exogen™ Compression Calf Sleeves, Sportboleh Sdh Bhd, Malaysia). Due to the loading increments available (200 and 300 g), exact loading magnitudes ranged from 0.90 – 1.11% BM. The load placement progressed through the training block from a proximal shank location to mid-shank and finished at a distal shank location. A summary of the training sessions and WR placement protocol are listed in Table 10, and the load placements are visualised in Figure 12. The control group completely the same sprint training, but without the addition of any WR.

Figure 12. Wearable resistance load placements



Note: A = proximal, B = mid, C = distal.

At the conclusion of each practice session, all athletes answered the question "how was your workout?" by selecting their response on a 0-10 modified Borg Rating of Perceived Exertion scale [38]. This allowed the research staff to monitor how the WR group was responding to the intervention to ensure the training session intensity did not extend beyond what was originally intended. This also allowed for an identification of any differences in perceived exertion between the control and WR groups.

Table 10. Training programme followed by both groups

	Session 1^	**Session 2**	**WR Placement and Magnitude^^**
Week 0	Pre-intervention Test (3×30 m)		
Week 1	4×22 m 8×10 m	4× Flying 28 m 5× Change of direction (15 m-diagonal cut-20 m) 1×80 m, 1×60 m, 1×50 m, 1×40 m	Proximal 1% BM
Week 2	5×22 m 11×10 m	Training session cancelled due to weather	Proximal 1% BM
Week 3	6×22 m 14×10 m	5× Flying 28 m 8× Change of direction (15 m-diagonal cut-20 m) 1×80 m, 1×60 m, 1×50 m, 1×40 m	Mid 1% BM
Week 4	5×22 m 11×10 m	5× Flying 28 m 6× Change of direction (15 m-diagonal cut-20 m) 1× 80 m, 1×60 m, 1×50 m, 1×40 m	Mid 1% BM
Week 5	6×22 m 13×10 m	5× Flying 28 m 8× Change of direction (15 m-diagonal cut-20 m) 1×80 m, 1×60 m, 1×50 m, 1×40 m	Distal 1% BM
Week 6	6×22 m 16×10 m	5× Flying 28 m 9× Change of direction (15 m-diagonal cut-20m) 1×80 m, 1×60 m, 1×50 m, 1×40 m	Distal 1% BM
Week 7	Post-intervention Testing (3×30 m)		

Note: ^ The 10 m sprints were completed from a variety of start positions (e.g. kneeling, lying). All other sprints were completed from a 2-point split stance start position. ^^ Wearable resistance (WR) was worn by the WR group in all sessions, whilst no WR was worn by the Control group in any sessions.

6.2.3 Data Analysis

The velocity-time data collected pre- and post-intervention were processed to calculate the horizontal force-velocity mechanical variables commonly used to profile an athlete's sprint running capabilities for each trial. The procedures utilised are extensively outlined elsewhere but in summary, the general mechanical ability to produce horizontal external force during sprint-running is portrayed by the linear F-v relationship [93]. The mechanical capabilities of the lower limbs are characterised by the variables: V_0, F_0, P_{max}, RF_{max}, and D_{RF} [86]. These mechanical profiling variables, along with sprint split times (5, 10, 20 and 30 m), maximal velocity of the measured sprint (V_{max}) and slope of the F-v profile (S_{FV}; $-F_0/V_0$), were calculated consistent with the method previously validated [74,93]. To represent athlete performance at a given testing timepoint, the calculated data from the three trials were averaged.

6.2.4 Statistical Analysis

A series of preliminary analyses (independent t-tests) were used to determine if there were significant differences between the control and WR group for each of the dependent variables at the pre-intervention testing time point. To determine the effect of the sprint training intervention (with or without the WR), a paired samples t-test was conducted for the dependent variables measured for each group. For each of the dependent variables, no outliers were found as assessed by inspection of a boxplot, except for an outlier in the control group S_{FV} data. This outlier was kept in the analysis as its inclusion did not change the paired-samples t-test conclusion. The differences between the pre- and post-intervention measures were normally distributed, as assessed by Shapiro-Wilk's test ($p > 0.05$) and Normal Q-Q Plot visual inspection. When an exception was found, the testing continued as the paired-samples t-test has been reported to be robust to violation of normality for Type I error [88].

To compare the control and WR group responses to the sprint training, a one-way analysis of covariance (ANCOVA) was conducted on post-intervention dependent variables with pre-intervention measures as the covariate [101,102]. For each dependent variable, there was a linear relationship between pre- and post-intervention measures and homogeneity of regression slopes as the interaction term was not statistically significant ($p > 0.05$). Standardized residuals for the interventions and overall model were normally distributed, as assessed by Shapiro-Wilk's test ($p > 0.05$). There was homoscedasticity and homogeneity of variances, as assessed by visual inspection of a scatterplot and Levene's test of homogeneity of variance ($p > 0.05$), respectively. There were no outliers in the data, as assessed by no variables with standardised residuals greater than ±3 standard deviations. A series of follow-up analyses (ANCOVA) were planned to compare the control and WR group responses to the sprint training with practice attendance as the covariate. However, attendance as a covariate was not linearly related to the dependent variable (post-intervention score) for each variable of interest, violating the linearity assumption for the ANCOVA test. Instead, Pearson's product-moment correlation was used to report on the relationship between practice attendance and difference scores (post – pre) for each of the dependent variables.

All data presented are unadjusted unless otherwise stated. Analyses were performed using SPSS Statistics (Version 25, IBM, Armonk, NY, USA). Significance was set at $p \leq 0.05$. ES statistics (Cohen's *d*) were calculated and described as trivial (<0.20), small (0.20), moderate (0.50) and large (0.80) [21].

6.3 Results

Twenty-two athletes completed the study (control group n = 10, 24.6 ± 2.99 years, 101.6 ± 34.7 kg, 178.8 ± 5.69 cm, baseline sprint time 4.30 ± 0.27 s and WR group n = 12, 22.6 ± 2.94 years, 96.5 ± 13.6 kg, 182.6 ± 8.60 cm, baseline sprint time 4.29 ± 0.13 s). Ten athletes were lost due to transfer to a different training squad (2), unrelated injury (2), or dropout from the team programme (6). A preliminary analysis was performed and confirmed that there were no significant differences between the control and WR group for each of the dependent variables at the pre-intervention testing time point. There were no significant differences for mass measures between the pre-intervention and post-intervention testing time points for either group. The exponential modelling of the velocity-time data was well fit with an average $R^2 = 0.98$ and all $R^2 > 0.95$. Mean and standard deviation for the sprint running time, speed, and mechanical determinants variables are presented in Table 11.

The results of the paired-samples t-tests are reported in Table 11. With regards to the control group, all variables were found to detrain significantly over the training period with the largest detraining effects (ES > 0.80) noted for F_0, S_{FV}, D_{RF}, RF_{max}, 5 m and 10 m times. In terms of the WR group, there were no significant changes to the recorded variables and any effects of training were trivial or small (all ES < 0.50).

Table 11. Pre- and post-intervention mean and standard deviation measures with within-group *p*-value and effect size statistics

	Control group (n = 10)			**WR group (n = 12)**		
	Pre	**Post**	**Post-Pre**	**Pre**	**Post**	**Post-Pre**
	$\bar{x}$ **(SD)**	$\bar{x}$ **(SD)**	***p*-value; ES**	$\bar{x}$ **(SD)**	$\bar{x}$ **(SD)**	***p*-value; ES**
Body mass (kg)	92.5 (12.9)	92.2 (13.0)	0.06; 0.02	96.5 (13.6)	96.1 (13.3)	0.06; 0.03
F_0 (N·kg^{-1})	7.87 (0.91)	6.73 (0.71)	<0.01*; 1.25	7.50 (0.69)	7.27 (0.65)	0.20; 0.33
P_{max} (W·kg^{-1})	17.3 (2.52)	15.3 (1.94)	0.01*; 0.79	16.6 (1.68)	16.3 (1.84)	0.48; 0.18
V_0 (m·s^{-1})	8.83 (0.73)	9.18 (0.64)	<0.01*; 0.48	8.90 (0.58)	9.01 (0.67)	0.26; 0.19
S_{FV} (%)	–83.0 (15.7)	–68.1 (14.3)	<0.01*; 0.95	–81.7 (14.1)	–77.9 (13.0)	0.10; 0.27
D_{RF} (%·s·m^{-1})	–8.07 (0.98)	–6.73 (0.85)	<0.01*; 0.37	–7.67 (0.85)	–7.36 (0.78)	0.11; 0.36
RF_{max} (%)	52.0 (3.39)	48.0 (3.08)	<0.01*; 1.18	50.9 (2.56)	50.2 (2.75)	0.28; 0.27
5 m time (s)	1.27 (0.08)	1.37 (0.07)	<0.01*; 1.25	1.30 (0.07)	1.32 (0.07)	0.38; 0.29
10 m time (s)	2.04 (0.11)	2.14 (0.10)	0.01*; 0.91	2.07 (0.08)	2.08 (0.08)	0.42; 0.20
20 m time (s)	3.33 (0.19)	3.45 (0.15)	0.02*; 0.63	3.37 (0.12)	3.38 (0.15)	0.60; 0.08
30 m time (s)	4.54 (0.28)	4.64 (0.21)	0.05*; 0.36	4.57 (0.17)	4.58 (0.21)	0.77; 0.06
V_{max} (m·s^{-1})	8.41 (0.60)	8.57 (0.49)	0.01*; 0.27	8.44 (0.43)	8.52 (0.51)	0.33; 0.19

Note: * = within-group significant differences ($p \leq 0.05$)

The ANCOVA test was used to determine differences between groups on post-intervention measures. The results are reported in Table 12. After adjustment for pre-intervention measures, significant between group differences of a large effect were found for all variables except V_0, 30 m time, and V_{max}.

Table 12. Adjusted mean difference scores for post-intervention measures with pre-intervention measures as a covariate with results of the one-way ANCOVA for between-group *p*-value and effect size statistics

	WR-Control		
	Mean difference	***p* value**	**ES**
F_0 ($N{\cdot}kg^{-1}$)	0.71	0.01*	1.17
P_{max} ($W{\cdot}kg^{-1}$)	1.45	0.02*	1.08
V_0 ($m{\cdot}s^{-1}$)	–0.23	0.07	0.82
S_{FV} (%)	–10.8	0.01*	1.33
D_{RF} ($\%{\cdot}s{\cdot}m^{-1}$)	–0.83	0.01*	1.21
RF_{max} (%)	2.80	0.02*	1.15
5 m time (s)	–0.07	0.01*	1.17
10 m time (s)	–0.08	0.02*	1.03
20 m time (s)	–0.09	0.05*	0.89
30 m time (s)	–0.08	0.11	0.71
V_{max} ($m{\cdot}s^{-1}$)	–0.08	0.36	0.41

Note: * = between-group significant differences ($p \leq 0.05$)

There were no significant differences in athlete RPE or attendance scores between the control and WR groups. The average reported RPE scores were 6.62 ± 0.86 for the control group and 6.58 ± 0.86 for the WR group. Athletes in the control group attended 66.4 ± 25.0% of practices, whilst athletes in the WR group attended 65.9 ± 18.6% of practices. There were no statistically significant correlations between attendance and difference score for any variable for either the control or WR group (r < 0.35 for all variables).

6.4 Discussion

This study determined the effects of a 1% BM lower-limb WR sprint running training intervention on performance measures in athletes. The main findings were: 1) the control group experienced significant detraining over the course of the intervention with large detraining effects (ES > 0.80) noted for F_0, S_{FV}, D_{RF}, RF_{max}, 5 m and 10 m times; 2) the use of WR enabled the WR group to retain pre-intervention magnitudes for the variables of interest over the course of the intervention with all changes being non-significant and considered trivial to small; 3) WR training proved superior to unloaded training in maintaining all the F-v variables of interest with the exception of V_0, 30 m time, and V_{max}; and 4) RPE was similar between groups. The hypothesis that the WR training would decrease sprint running time, increase velocity, and positively influence the horizontal force-velocity mechanical variables was therefore rejected.

The control group was found to detrain across several variables suggesting there was insufficient recovery time between training sessions or the sprint training protocol was insufficient to provide a training stimulus to maintain or improve performance. Sufficient recovery and training frequency are required to produce muscular performance adaptation [91]. It is unlikely the recovery time between training sessions was insufficient or that a general fatigue status increased due to sudden exposure to pre-season training as the WR group did not display the same decrement in performance over the training period. Whilst the exact training frequency required to maintain sprint performance through sprint training alone is not known, a training frequency of 2-3 times per week has been suggested to produce sprint performance improvements using resisted sled training [1]. The consideration of training frequency cannot be made without the consideration of training session volume and intensity (i.e. volume load). The athletes in this study were allocated two sprint training sessions a week through the pre-season; this volume load was thought to be adequate to maintain or improve performance capabilities for the allocated training frequency. However, attendance rates were low (control group = 66.4%, WR group = 65.9%), resulting in a lower training frequency than initially prescribed for many of the athletes. It appears that the use of WR increased the volume load of each training session, reaching a threshold necessary to maintain performance capabilities for the short distance sprint running measured in this study.

Although our hypothesis was rejected, the WR used in this study provided an adequate training load to retain sprint performance and mechanical capabilities for the intervention group athletes and this WR training was superior to the unloaded training in maintaining the variables of interest except for 30 m sprint times, V_{max}, and V_0. It seems that WR training could be used to increase training load when sprint specific training frequency is low, which often occurs during pre-season and in-season time frames. This idea is supported by previous work that has found that carrying an additional load on the limb during running is associated with an increased physiological cost and directly affects the mechanical work needed to move the limb segments [65,66]. There is also the possibility that WR training provides a unique training stimulus to influence sprint running. The micro-loading inherent to WR training allows the athletes to perform the sprint running movement pattern under resistance at or near unloaded movement velocities [36,54,56]. This is a valuable consideration when planning training as the velocity adaptations that occur with resistance training are greatest at or near the velocity of the training performed [5] and sprint running requires rapid muscular force production.

Proficiency for faster sprint running acceleration relies on the ability to apply high levels of force to the ground and to orientate the force vector in a more horizontal direction [23,86]. The F-v profile was used in this study to quantify these abilities and showed that WR training was effective in maintaining F_0, whilst there was no difference between groups in the change in V_0 across the intervention. The lack of difference in the change in V_0 between the control and WRT groups suggests that this factor is less affected by detraining but may require a different type of intervention for enhancement. An athlete’s technical ability to apply force into the ground with increasing speed is quantified using D_{RF} [73], which has been shown to be significantly correlated to maximal speed, mean 100 m speed, and 4 second distance measures [72,71]. Athletes in the control group experienced a large change in D_{RF} (–16.6%) indicating a less steep decline in the ratio of force for a given increase in speed which could potentially be considered a technical improvement. However, this should be interpreted with respect the large decrease in RF_{max}

(−7.69%, ES = 1.18) and the small increase in V_{max} (1.90%, ES = 0.27). Changes to these variables indicate that, rather than being a higher ratio of force for a given speed, the ratio of force was lower at all speeds in post-testing until speeds approaching V_{max}. This global change in sprint performance impacted D_{RF}, and the D_{RF} change in this instance should not be considered a technical performance improvement when considered in the context of the other changes to the mechanical output variables and the resulting significant increase in sprint times. Athletes in the WR group experienced no significant changes to these variables. Overall examination of these significant between group differences point to the mechanical output changes which are influenced with shank WR training – it appears that WR training offers a means to maintain an athlete's technical ability to produce horizontal force at low velocities and maintain a horizontally oriented ground reaction force with increasing speed. These technical abilities are particularly applicable for field-based sport athletes where short distance acceleration is a valuable performance attribute and can carry greater importance than maximal speed ability for some playing positions.

Session RPE was used to monitor athlete response to the training loads. These data provided information throughout the training intervention time frame to monitor the WR group's response to completing the sprint running protocol with additional limb load (compared to the control group), and to determine how the progressive overload of moving the WR placement distally was handled. There were no differences in average RPE scores between the two groups. This is surprising as information from previous research [65,66] and anecdotal athlete feedback has indicated an increased difficulty in performing running with lower-limb WR. It may be that session RPE does not provide the sensitivity needed to distinguish objective differences in training loads associated with lower-limb WR training, or that a 1% BM WR loading scheme allows the athletes to complete a relatively higher training load without an increase in perceived exertion. RPE has been reported as a valid measure to indicate exercise intensity [41] but any potential relationship between WR training induced changes in RPE and objective internal workload measures has yet to be investigated.

A limitation of this study was the low attendance rates which resulted in a lower training volume than what was prescribed to improve performance through the pre-season. It is unknown if an increase in performance would have occurred with the WRT beyond the unloaded training if the athletes attended all prescribed training sessions. Another limitation was the lack of specificity between the training and testing protocol running distances. Researchers have previously suggested that separate training strategies may need to be employed to elicit improved sprint running times for different distances [3]. The training protocol employed in this study used a variety of running distances (10–80 m) whilst the testing protocol measured one sprint distance (30 m). It is unknown how the athletes' sprint times changed over longer distances (40–80 m). Future work to understand the effects of lower-limb WR training for sprint running should consider investigating the necessary exposure to WR training needed to elicit sprint running performance improvements, potential changes to step and joint kinematics, and how to best quantify the internal and external workload changes associated with different WR magnitudes and placements for applied scenarios.

6.5 Conclusions

The athletes that completed the WR training intervention did not significantly improve (or decrease) in sprint running times or velocity. However, comparatively, these athletes were able to maintain baseline performance whilst the control group experienced detraining of mechanical output and sprint times. These results suggest a 1% BM lower-limb WR training intervention is sufficient to provide a training stimulus that retains sprint qualities, which is superior to training with no load. However, the volume or frequency of exposure needed to produce an increase in performance following introduction of the training stimulus is still unknown.

Chapter 7. Comparison of the 1080 Sprint to Radar for Obtaining Horizontal Force-Velocity Profile Variables During Sprint Running

This chapter comprises the following manuscript, which is under review at the International Journal of Sports Science and Coaching.

Feser EH, Lindley K, Clark K, Bezodis N, Korfist C, Cronin JB. Comparison of the 1080 sprint to radar for obtaining horizontal force-velocity profile variables during sprint running. *Int J Sports Sci Coach*. (under review).

Author contribution: Feser 82%, Lindley 6%, Clark 4%, Bezodis 4%, Korfist 2%, Cronin 2%

7.0 Prelude

Field-based performance measures can be advantageous to laboratory-based performance measures as they capture athlete performance within their training environment (ecological validity) and often allow for measurement of sport-specific movements that can't be performed in constrained spaces. For sprint running, technologies that record velocity at high sample rates can provide considerable detail regarding the athlete's entire sprint performance. A newer piece of technology, called a 1080 Sprint, can be used to measure an athlete's velocity-time curve during sprint running. However, minimal information was available regarding the measurement accuracy of the device or its ability to produce measures similar to other commonly used field-based measurement devices (e.g. a radar gun). Given the multi-site nature of the research undertaken in this thesis, it was of interest whether the 1080 Sprint could be used interchangeably for field-based research measures, which led to establishing the agreement between the horizontal F-v profile variables obtained from 1080 Sprint to those obtained from a Stalker ATS II during a 30 m sprint run, the results of which are presented in this chapter. More specifically, it was anticipated that the 1080 Sprint would be used in addition to a radar gun for the data collection of additional assessment time points in the remainder of the projects for this thesis (i.e. Chapter 8 and a follow-up study, which was cancelled due to pandemic-related school closures). Understanding the interchangeability of the data from these devices was important prior to committing to using the 1080 Sprint, thus the rationale for this brief report. Further, this chapter provided practical information for coaches interested in using a 1080 Sprint for horizontal force-velocity profiling and outlines a technique to handle questionable data around the onset of movement for the sprint, which was further described in Chapter 8.

7.1 Introduction

Temporal measurement of athlete sprint running performance can be used to determine the horizontal F-v relationship during sprint running [73,74,93]. A radar device is often the technology of choice to record the velocity-time data needed to calculate the horizontal F-v relationship [98] and has been used in research with sprint [72], rugby [29,55], and soccer [93] athletes. A 1080 Sprint device (1080 Motion, Lidingö, Sweden) is another piece of technology that has become available for commercial use and can measure an athlete's velocity-time curve during sprint running. The 1080 Sprint features a servo motor attached to a spooled cable that can be used with the accompanying software as a robotic resistance or towing device. The system is described in the user manual to have an optical encoder that is attached to the motor axis to measure the speed of the cable movement which is recorded by the accompanying software. It is assumed that the speed of cable can be used as a surrogate measure for athlete velocity during linear sprint running since the cable is attached to the athlete with a waist harness.

Considering the recent research interest in the 1080 Sprint as a training tool [15,45,52,63,87,100] and measurement device [30] and given its increasing use by coaches and sport scientists, it seems prudent to establish the agreement between data calculated from the 1080 Sprint and an alternative technology widely used in practice, a radar device. This would provide researchers, coaches, and sport scientists with the necessary information to determine if the agreement between the devices is acceptable within the context of their specific application. Therefore, the purpose of this study was to establish the magnitude of systematic bias and random error of horizontal F-v profile variables obtained from 1080 Sprint to those obtained from a widely used radar device (i.e. Stalker ATS II) during a 30 m sprint run.

7.2 Methods

7.2.1 Procedures

Twenty athletes volunteered to participate in this study (mean ± SD; age: 16.5 ± 0.51 years, stature: 180 ± 6.73 cm, mass: 71.2 ± 8.11 kg). The athletes were all members of the same high-school American football training group. Inclusion criteria required athletes to be currently training and categorised as a position player other than an offensive or defensive lineman. Athletes were excluded if they were under the age of 16, had a current or previous injury that may be further aggravated by participating in the study, or did not pass the Physical Activity Readiness Questionnaire. All study procedures were approved by the host University Institutional Review Board. Participants provided written informed consent and parental assent before participating in the study.

The testing session started with a warm-up protocol that mimicked the athletes' usual practice session preparation. Following the warm-up, each athlete completed a maximal effort 30 m sprint performed from a two-point, split stance position. Two devices were simultaneously used to measure athlete velocity, a Stalker ATS II radar device and a 1080 Sprint motorised resistance device. The radar device (Stalker ATS II, Applied Concepts, Dallas, TX, USA) was positioned 5 m directly behind the starting line at a height of 1 m to approximate the athletes' centre of mass location. STATS software (Version 5.0.2.1, Stalker ATS II, Applied Concepts, Dallas, TX, USA) was used to collect the radar data at 46.875 Hz. The cable of the 1080 Sprint was attached to the athlete with a waist harness and the device was placed on the floor 1.5 m behind the starting line. Per manufacturer recommendations, all trials were completed with the 1080 Sprint in Isotonic mode. The minimum load setting of 1 kg was utilised, necessary for the device to function and thought to be required to maintain tension on the cable. Quantum software (1080 Motion, Lidingö, Sweden) was used to collect the 1080 Sprint data at 333 Hz.

The raw velocity-time data was exported from both software programmes. A custom-made MATLAB script (MATLAB R2019b, The MathWorks, Inc., Natick, Massachusetts, USA) was used to calculate individual linear F-v profiles by first fitting the velocity-time data from 1.5 m/s to the estimated 30 m end-of-sprint with an exponential equation following the method presented in Morin et al. [74]. Following, outlier samples were identified by a residual function to remove data points ≥ ± 2 × standard deviation of the residual and the exponential equation was fit again. From this exponential fit, the related variables of V_0, F_0, P_{max}, and $S_{FV(BM)}$ were computed. The variables used in the exponential modelling of each F-v profile, time constant tau and horizontal maximal velocity (V_{Hmax}), were also recorded.

7.2.2 Statistical Analysis

Means and standard deviations were calculated to represent the centrality and spread of the calculated variables. The variables calculated from the 1080 Sprint velocity-time data were compared to the variables calculated from the radar by determining the bias (mean measurement difference between the devices, 1080 Sprint – Radar) and random error (1.96 × standard deviation of the differences between the devices), and the 95% limits of agreement [11].

7.3 Results

The velocity-time data from the 1080 Sprint was unable to be modelled within the time domain of the recorded sprint for five athletes by the exponential function fitting process used. This was identified by the modelled velocity not reaching a start value of 0 m/s within the researcher defined time frame of when movement onset should occur for the sprint trial (see Figure 13 as an example). These athletes were removed from all analyses resulting in 15 remaining athletes. The exponential modelling of the velocity-time data was fitted with an average R^2 = 0.97 and all R^2 > 0.96 for the radar-derived data and an average R^2 = 0.97 and all R^2 > 0.91 for the 1080 Sprint-derived data.

Mean and standard deviation of the variables calculated are presented in Table 13 along with the bias and random error values. A positive bias, indicating a higher measurement by the 1080 Sprint, was found for tau, V_{Hman} and V_0. For P_{max}, the bias measurement resulted in a value of <0.01 W/kg, however, the corresponding random error value (± 0.94 W/kg) represented a range of ± 7.09% of the mean P_{max} value measured by the radar. The velocity-time data simultaneously recorded for one athlete's sprint trial along with the corresponding exponential model can be found in Figure 14.

Figure 13. An example of the horizontal velocity recorded by the 1080 Sprint (solid line) and the corresponding exponential modelled velocity (dashed line) which could not be modelled within the time domain of the recorded sprint for one athlete's sprint trial

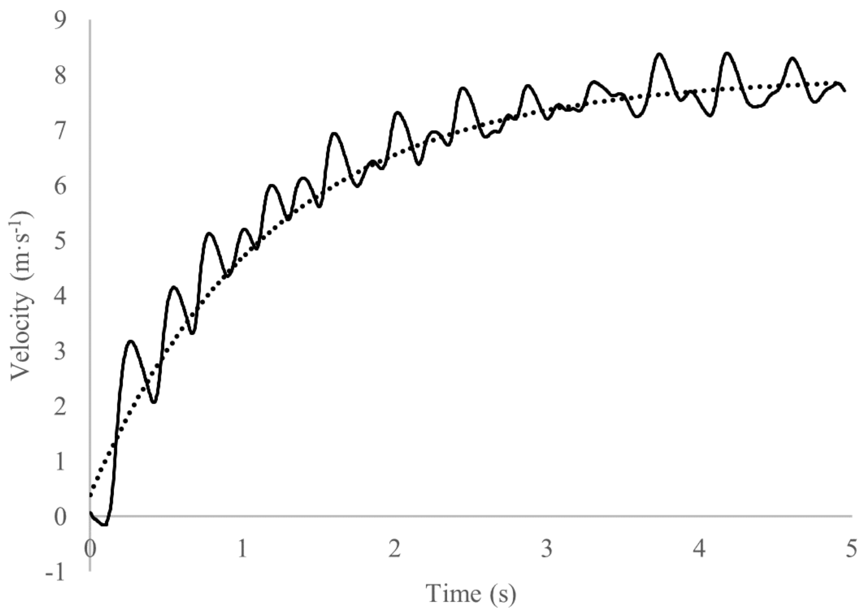
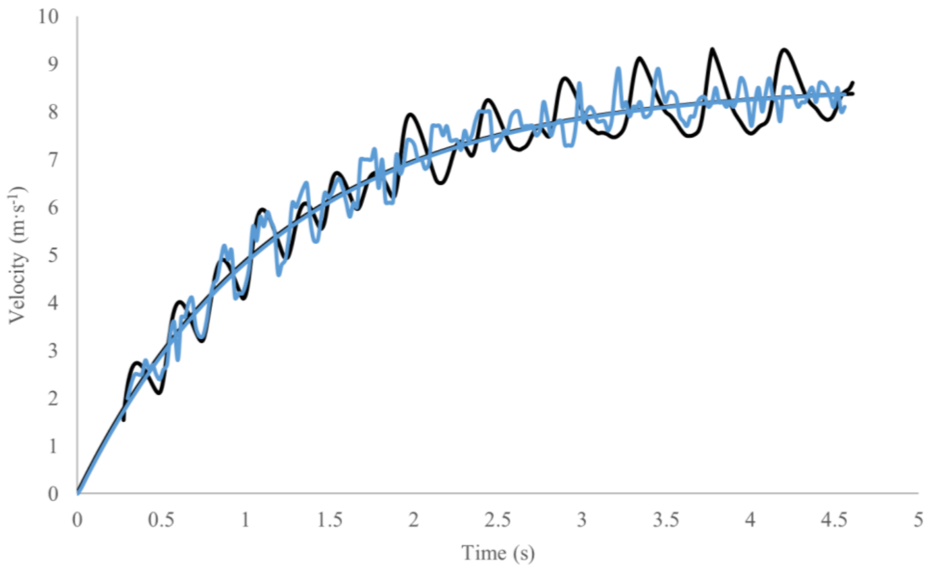


Table 13. Device measurements (mean ± SD) and between device bias, random error, and limits of agreement

	1080 Sprint	Radar	Ratio (1080 Sprint/radar)	Bias*	Random Error	95% LOA
Tau (s)	1.17 ± 0.09	1.10 ± 0.09	1.06	0.07	± 0.11	(–0.04, 0.18)
V_{Hmax} (m·s^{-1})	7.80 ± 0.69	7.66 ± 0.69	1.02	0.14	± 0.19	(–0.05, 0.34)
F_0 (N/kg)	6.61 ± 0.36	6.75 ± 0.40	0.98	–0.14	± 0.64	(–0.77, 0.50)
V_0 (m·s^{-1})	8.08 ± 0.74	7.92 ± 0.74	1.02	0.16	± 0.23	(–0.07, 0.39)
$S_{Fv(BM)}$ (%)	–0.82 ± 0.07	–0.86 ± 0.08	0.95	–0.04	± 0.11	(–0.07, 0.14)
P_{max} (W/kg)	13.3 ± 1.69	13.3 ± 1.69	1.00	<0.01	± 0.94	(–0.94, 0.94)

Note: * = A positive bias indicates a higher measurement by the 1080 Sprint device than the radar device; LOA = limits of agreement.

Figure 14. The horizontal velocity simultaneously recorded by the radar (blue) and 1080 Sprint (black) for one athlete's sprint trial is presented with the corresponding exponential modelled velocity



7.4 Discussion

This study established the magnitude of systematic bias and random error between horizontal F-v profile variables obtained from a 1080 Sprint to that obtained from a radar during a 30 m sprint run. As previously mentioned, the velocity data recorded with the 1080 Sprint for five athletes were unable to be modelled by the exponential equation fitting process used.

The calculation of systematic bias for the horizontal F-v profile variables resulted in positive bias (indicating a higher measurement by the 1080 Sprint) for tau, V_{Hman} and V_0. All bias values were within a 6.36% difference between the devices. While some lack of agreement is generally expected when quantifying performance measures from different measurement methods, the amount by which the methods differ is important for practical interpretation [11]. In addition to the bias score calculation, the 95% limits of agreement were provided to give insight into the range in which most differences between the two devices will lie. The limits of agreement should be considered alongside the bias scores. This is most evident when evaluating the agreement between the devices for P_{max}. Although no bias was measured (<0.01), the random error value (± 0.94 W/kg) represented a range of ±7.09% of the mean P_{max} radar value.

The horizontal F-v relationship is useful for gaining insight into the sprinter's mechanical effectiveness during sprint running but is reliant on a macroscopic model of the centre of mass velocity [93]. In this study, 25% of the sprint trials captured by the 1080 Sprint device were unable to be modelled with the exponential equation fitting process. Post analysis visual inspection of the raw velocity data recorded by the 1080 Sprint shows a very rapid rise in velocity following movement onset. It is possible the velocity data recorded by the 1080 Sprint does not well match the athlete's true centre of mass velocity during this initial portion of the sprint, which challenged the model fitting process. A similar limitation has been previously reported with velocity estimates from a laser-based device [8], although this would theoretically also be the case for the radar. On the 1080 Sprint machine, the lowest load setting (1 kg) was used to reduce restriction of the athletes' maximal performance and in an attempt to record true maximal performance values. However, with this load setting, slack is easily developed in the line and this could be an additional contributing factor to any error between the measured velocity values and the true velocity of the athlete's movement. A greater load setting would increase the tension between the athlete and the machine to reduce excessive motion of the cable. But it is unknown how a higher load setting could hamper maximal performance resulting in a different F-v profile calculation and limiting the comparison to measures from different devices.

The accuracy of the F-v profiling computation is dependent on successful identification of movement onset [94]. It is important to note that in this study we systematically removed questionable data around movement onset by use of a velocity-based threshold and the model fit was extended backwards to produce true movement onset for all sprint trials. This permitted a consistent application of the modelling approach for both the radar and 1080 Sprint data. Thus, the findings of this study are applicable when a similar approach is utilised. Any perceived limitations of the 1080 Sprint presented here should not be viewed as an overarching reflection of the viability of the machine use in general. Rather, this information is a cautionary note of the potential use and application of the data recorded under the conditions described here. Future research should endeavour to identify other processing approaches for F-v profiling with the 1080 Sprint velocity data that are successful for all trials.

7.5 Implications

The data presented in this study provide practitioners with the level of systematic bias and measurement error present when using the above-described approach to F-v profiling with velocity data recorded from a 1080 Sprint and Stalker ATS II radar. Individual decisions should be made on whether the potential for error is acceptable within the intended application, including the variables of interest and the specific within- or between-athlete comparisons being made.

Chapter 8. The Effects of Lower-Limb Wearable Resistance on Sprint Performance in High School American Football Athletes: A Nine-Week Training Study

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Author contributions: Feser 82%, Korfist 7%, Lindley 5%, Bezodis 2%, Clark 2%, Cronin 2%

8.0 Prelude

One of the main findings from Chapter 6 was the superiority of WR training for retaining sprint qualities compared to training with no load during a low volume pre-season time period. Additionally, the utility of WR to increase within-session workloads when training time is constrained was made clear. However, the WR loading parameters necessary to elicit improvements in sprint running performance was still not understood. The purpose of this chapter was to determine the effects of a lower-limb WR training intervention implemented during an off-season, low volume training period on training outcomes. The load magnitude, placement, and progression scheme from Chapter 6 was utilised again with team sport athletes. However, the duration of the intervention was expanded to nine-weeks. Also, from Chapter 7 it was concluded that horizontal F-v profile variables obtained from the 1080 Sprint were not exactly comparable to those obtained from a radar device, but more importantly, the velocity data of 25% of the athletes measured were unable to be modelled by the exponential equation fitting process. This rendered the 1080 Sprint not suitable for the purposes of this study. Therefore, it was decided not to bolster the study findings with additional measurement timepoints which were only available if using the 1080 Sprint (i.e. mid-training and 2-weeks post-training). Additionally, from this chapter, practical recommendations for coaches interested in using lower-limb WR training to increase in-session workloads during periods of low volume training were offered.

8.1 Introduction

Coaches and strength and conditioning practitioners are often faced with training time constraints resulting from athlete schedules, organisation rules, and priority of concurrent tactical and technical training. This results in a challenge to fit the desired strength and conditioning programming within the allotted training time frames and often compromises aspects of the programming. To address this challenge, it is imperative to fully optimise the allotted strength and conditioning training time [39]. How to accomplish this varies based on the season within the athletic calendar as time constraints change and must be balanced against the foci of the season itself. For example, the NCAA Division I Athletics programme only allows 20 hours a week of countable athletically related activities during the in-season [82] and lower level sporting groups may only hold three 75 minute training sessions a week in the off-season (e.g. high school football). During the off-season, the focus of the strength and conditioning training is to develop multiple fitness qualities (e.g. strength, metabolic endurance, speed) while during the in-season, the focus is on the development of expressing these fitness qualities within sport-specific practice. Ultimately, when coaches and strength and conditioning practitioners are presented with the need to optimise reduced strength and conditioning training time, two smart options to do so include: 1) closely match the training to the technical demands of the sport; and/or, 2) increase within-session workloads.

WR is a training modality that can be used to accomplish these options [31,36,54,56]. This has mostly been applied to the lower-limb by attaching an external load, as little as 0.5% BM, onto the athlete’s thigh and/or shank allowing them to perform the movement task of interest under resistance. This makes training with lower-limb WR particularly applicable for matching the technical demands of linear and multi-directional sprint running for field-based sports and track and field athletes and has been suggested as a tool to improve speed performance [31,36,56]. With lower-limb WR, the athlete can train under resistance at high movement velocities while performing sprint running or related technical drills thus maintaining a high level of specificity to closely match the involved muscles, contraction speeds, and joint ranges of motion of the movement task of interest, e.g. sprint running. Given this, it seems that lower-limb WR offers a high level of training specificity to optimise the transference of any strength and metabolic improvements to sprint running performance [25]. However, the utility of WR within programmes that have time constraints placed upon them is unknown.

Lower-limb WR can also be used to increase the within-session workload by performing the prescribed movement tasks with the added limb load at or near the same movement velocity [31]. This increases the mechanical, and therefore muscular, work requirements to perform the movement tasks [65,66]. The increases in muscular work that coincide with the addition of the lower-limb WR produce an increased metabolic cost of performing the movement task [66]. Using lower-limb WR during running has therefore been reported to increase oxygen consumption and heart rate, and these metabolic and mechanical changes are increased when load magnitude increases or placement becomes more distal on the limb [65].

Research on longitudinal outcomes of lower-limb WR training for sprint running with athletes is limited to two randomised control longitudinal studies and one single subject case study completed to-date. When 200–600 g of shank WR was used during the warm-up of pre-season training sessions for 16–18 year-old provincial level soccer players, the WR training was found to be more effective in reducing 10 m and 20 m sprint times compared to completing the warm-up with no WR following an 8-week training cycle [12]. In the second longitudinal study, when 1% BM shank WR was used during sprint-specific training sessions with collegiate and semi-professional rugby athletes, the WRT was found to be more beneficial in maintaining baseline sprint performance measures compared to the control group which wore no WR during the training and experienced significant detraining of performance variables over the 6-week pre-season training period [35]. Lastly, introducing 2% BM thigh WR into a recreational athlete's sprint training regime substantially improved 40 m sprint times after a 5-week training period [57]. These findings provide evidence that the adaptations from lower-limb WR training transfer to sprint running performance [12,57] and help retain fitness qualities that detrain with inadequate training frequency [35]. This further suggests that lower-limb WR is a viable training option to optimise the strength and conditioning training time allotments.

While researchers have started to uncover the effects of lower-limb WR training with athletes, further information on how athletes respond to WR training interventions and what is the minimal worthwhile dose to elicit particular fitness qualities is necessary for coaches and strength and conditioning practitioners to better understand how to incorporate WR within their training programmes. In particular, it is of interest to further understand how to capitalise on the benefits of WR training to influence athlete speed capabilities during periods of constrained training time. Therefore, the purpose of this study was to determine the effects of a lower-limb WR sprint running training intervention on athlete speed capabilities following a nine-week off-season, low volume training period for American football high school athletes. We hypothesised that the WR training would decrease sprint running time, increase velocity, and increase the horizontal F-v mechanical variables beyond the changes seen from training with no WR.

8.2 Methods

8.2.1 Participants

Twenty-five athletes volunteered to participate in this study and were all members of the same American high school football team. Inclusion criteria required athletes to have a minimum of one year of resistance training experience, be currently training, and be categorised as position player other than an offensive or defensive lineman. Athletes were excluded if they were under the age of 16, had a current or previous lower extremity injury that may be further aggravated by participating in the training or did not pass the Physical Activity Readiness Questionnaire. After attrition due to failure to attend post-testing (2), unrelated injury (1), or drop out from the team programme (3), nineteen athletes completed the study. Eight athletes completed the unloaded training intervention, i.e. control group (age = 16.3 ± 0.46 years, mass = 69.3 ± 7.16 kg, height = 177 ± 6.92 cm) and eleven athletes completed the WR training intervention (age = 16.6 ± 0.50 years, mass = 76.5 ± 4.60 kg, height = 183 ± 5.18 cm). Training programme adherence was above 80% for all athletes included in the results. All study procedures were approved by the host University Institutional Review Board.

8.2.2 Performance Testing

The athletes reported to an indoor fieldhouse to complete the pre- and post-intervention performance testing. Each testing session started with a warm-up protocol consistent with the athletes' typical practice session preparation. Following this, each athlete completed two maximal effort 30 m sprints, separated by a minimum of five minutes of rest. Each sprint was performed from a two-point, split stance start position, and was initiated by the athlete when they felt ready. A radar device (Stalker ATS II, Applied Concepts, Dallas, TX, USA) was used to measure athlete velocity at 47 Hz. The radar was positioned 5 m directly behind the starting position and at a vertical height of 1 m to approximately align with the participant's centre of mass [55]. STATS software (Version 5.0.2.1 Stalker ATS II, Applied Concepts, Dallas, TX, USA) was used to collect all data.

8.2.3 Training Intervention

The sprint training occurred in tandem with an off-season training block in which the athletes reported to three practice sessions a week. Each session started with a twenty-minute warm-up period that included skipping and hopping sprint running drills completed at a moderate intensity (four drills in total, each completed 2 × 30 m). After the warm-up, the athletes participated in the sprint training session that was followed by a weight training session. The athletes were match-pair randomised into the WR and control groups using the pre-intervention 30 m sprint times (control group baseline sprint times = 4.91 ± 0.24 s and WR group baseline sprint times = 4.87 ± 0.30 s) measured by an automatic dual-beam timing system (Swift Speed Light, Swift Performance Equipment, Wacol, Australia). The WR group completed two of the three weekly sprint training sessions with 1% BM load attached to the shank with a specialised compression garment (Lila™ Exogen™ Compression Calf Sleeves, Sportboleh Sdh Bhd, Malaysia). Due to the loading increments available (200 and 300 g), exact loading magnitudes ranged from 0.87–1.11% BM. The load was applied at the start of the warm-up period and not removed until the end of the training session. The load placement progressed through the training block from a proximal shank location to mid-shank and finished at a distal shank location to provide a progressive overload. The load placement and magnitude was chosen to be consistent with previous research [35]. A summary of the training sessions and WR placement protocol are listed in Table 14. An image of the load placements can be found in Figure 15. The control group completed the same sprint training, but without the addition of any WR or compression garments. There were some weeks in which a practice session was cancelled due to weather or a public holiday. For these weeks, the training sessions that included WR for the WR group were prioritised over the third training session of the week that did not include WR, with the control group completing the same training as the WR group but unloaded. Some training sessions for the WR and control groups included resisted sprints, meaning the WR group wore the WR while doing resisted sprints. A Run Rocket (Runrocket, San Antonio, Texas, USA) was used for the resisted sprints with a moderate level of resistance (one that would approximately double 20 m sprint times) maintained on this throughout the training study.

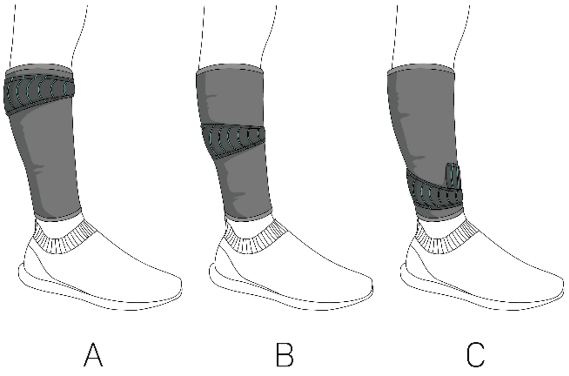
Table 14. Training programme followed by both groups

	Session 1	**Session 2**	**Session 3**
Week 0	Pre-intervention Test (2×30 m)		
Week 1	General sprint technique drills	Fly 10m 3×10 m Resisted sprint 3×30 m	4 sets of: Isometric split squat 5×5 s Hurdle jumps 5×5 hurdles Band assisted vertical jump 1×10
WR:	**Proximal 1%**	**Proximal 1%**	
Week 2	Cancelled due to public holiday	Fly 10m 3×10 m Mini hurdles 6×30 m	Fly 3×10 m Resisted sprint 3×30 m
WR:		**Proximal 1%**	**Proximal 1%**
Week 3	Cancelled due to weather	Cancelled due to weather	Fly 3×10 m Three-point start 3×10 m
WR:			**Proximal 1%**
Week 4	Fly 4×10 m Mini hurdles 6×30 m	Cancelled due to weather	Three-point start 4×20 m Resisted sprint 4×20 m
WR:	**Proximal 1%**		**Proximal 1%**
Week 5	Fly 3×10 m Mini hurdles 6×30 m	Three-point start 4×10 m Resisted sprint 4×20 m	4 sets of: Isometric split squat 5×5 s Hurdle jumps 5×5 hurdles Band assisted vertical jump 1×10
WR:	**Mid 1%**	**Mid 1%**	
Week 6	Cancelled due to public holiday	Fly 4×10 m Mini hurdles 8×30 m	Three-point start 4×20 m Resisted sprint 4×20 m
WR:		**Mid 1%**	**Mid 1%**
Week 7	Fly 4×20 m Mini hurdles 8×30 m	Three-point start 4×20 m Resisted sprint 4×20 m	4 sets of: Eccentric split squat 5×5 s Hurdle jumps 5×5 hurdles Band assisted vertical jump 1×10
WR:	**Mid 1%**	**Mid 1%**	
Week 8	Fly 3×20 m Mini hurdles 6×30 m	Three-point start 3×30 m	4 sets of: Eccentric split squat 5×5 s Hurdle jumps 5×5 hurdles Band assisted vertical jump 1×10
WR:	**Distal 1%**	**Distal 1%**	
Week 9	Fly 4×20 m Mini hurdles 6×30 m	Three-point start 5×30 m	4 sets of: Eccentric split squat 5×5 s Hurdle jumps 5×5 hurdles Band assisted vertical jump 1×10
WR:	**Distal 1%**	**Distal 1%**	

Week 10	Post-intervention Test (2×30 m)	

Note: Wearable resistance (WR) was worn by the WR group in the sessions indicated above, whilst no WR was worn by the Control group in any sessions.

Figure 15. Wearable resistance placements



Note: A = proximal, B = mid, C = distal

8.2.4 Data Analysis

To produce a profile of the athletes' sprint running capabilities at the pre- and post-intervention time points, the velocity-time data collected were processed to calculate horizontal force-velocity mechanical variables. All processing was done in a custom-made MATLAB script (MATLAB R2019b, The MathWorks, Inc., Natick, Massachusetts, USA). Questionable data around movement onset [94] was removed by applying a 10-sample rolling average to the raw velocity-time data and identifying where the athlete reached 1.5 m/s. The raw velocity-time data from this point onwards was then fit with a mono-exponential function to model the centre of mass velocity of the athlete as a function of time. The procedures utilised are extensively outlined in Samozino et al. [93]. To best fit the mono-exponential function given the uncertainty in where the true movement onset occurred, movement of this function in the time domain was permitted in the model-fitting operation [94]. This produced theoretical velocity-time data beginning at 0 m/s at t = 0 s, and ending at the estimated 30 m end-of-sprint. Outlier samples in the raw velocity-time data were then identified by a residual function which removed data points ≥ ± 2 × standard deviations of the residual. The mono-exponential function was then fit again to the remaining data to obtain the final modelled velocity-time profile. Two athletes clearly showed a reduction in velocity before reaching 30 m during the pre-intervention testing. The velocity-time data for their trials was manually trimmed at the end of the velocity plateau prior to data analysis. This resulted in a n = 7 for the control group and n = 10 for the WR group for the 30 m sprint time dependent variable as the modelled data for these two athletes did not reach 30 m. The final mono-exponential modelling of the velocity-time data was well fit to the raw data with an average $r^2 = 0.97$ and all $r^2 > 0.94$.

To describe the general mechanical ability to produce horizontal external force during sprint-running the individual linear F-v profiles were computed [93]. From this, a series of variables were used to describe the mechanical capabilities of the lower limbs: theoretical maximum velocity V_0, F_0, P_{max}, RF_{max}, and D_{RF} [86]. These mechanical profiling variables, along with sprint split times (5, 10, 20 and 30 m), V_{max}, and $S_{FV(BM)}$, were calculated consistent with the method previously validated [74,93]. To represent athlete performance at a given testing timepoint, the calculated variables from the two trials were averaged.

8.2.5 Statistical Analysis

Means and standard deviations were calculated to represent centrality and spread of the dependent variables. The differences between the pre- and post-intervention measures for both groups were normally distributed (assessed by Shapiro-Wilk's test, all $p > 0.05$) and no outliers were present (assessed by inspection of a boxplot). To describe individual responses to the training intervention, the SWC was calculated as 0.2 × pre-intervention between-subject standard deviation. The individual training responses were then classified as an increase (> + SWC) or decrease (> – SWC) for each dependent variable if the individual change from the pre-intervention measure was outside of the SWC threshold, and a trivial change if it remained within the SWC [21].

To compare the control and WR group responses to the sprint training, an ANCOVA was conducted on post-intervention dependent variables with pre-intervention measures as the covariate [101,102]. Evaluation of the homogeneity of regression slopes assumption found that the relationship between each covariate and dependent variable was not significantly different between groups ($p > 0.05$). Standardised residuals for the interventions and overall model were normally distributed, as assessed by Shapiro-Wilk's test ($p > 0.05$). There was homoscedasticity and homogeneity of variances, as assessed by visual inspection of a scatterplot and Levene's test of homogeneity of variance ($p > 0.05$), respectively. There were no outliers in the data, as assessed by no variables with standardised residuals greater than ±3 standard deviations.

All data presented are unadjusted unless otherwise stated. Analyses were performed using SPSS Statistics (Version 25, IBM, Armonk, NY, USA). Significance was set at $p \leq 0.05$. Effect size (ES) statistics (Cohen's *d*) were calculated and described as trivial (<0.20), small (0.20), moderate (0.50) and large (0.80) [21].

8.3 Results

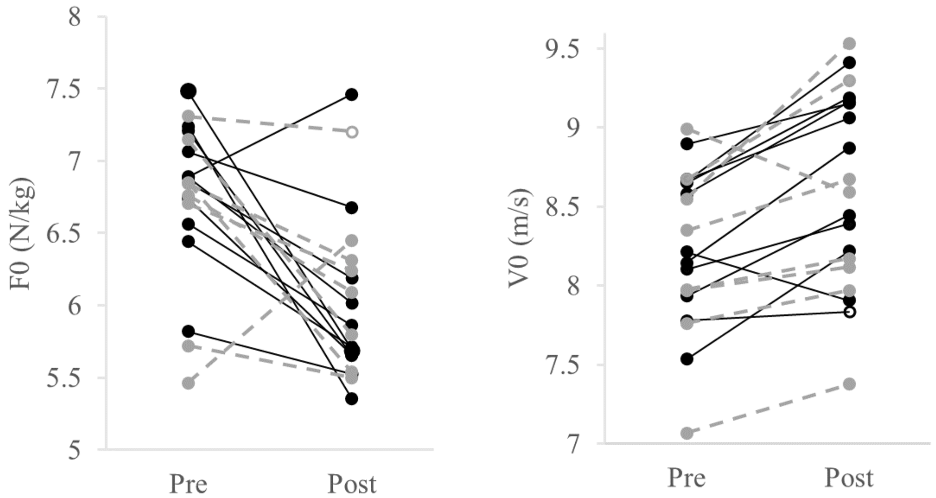
Mean, standard deviation, and individual training response for the sprint running time, speed, and horizontal F-v mechanical variables are presented in Table 15. The majority (≥ 50%) of the athletes in both groups were found to increase V_0, S_{FV}, D_{RF}, V_{max}, 5 m, 10 m, and 20 m times and decrease F_0, P_{max}, and RF_{max} over the training period. The pre- and post-intervention F_0 and V_0 results for each individual are presented in Figure 16.

Table 15. Pre- and post-intervention mean and standard deviation measures with individual training response classification

		Pre	Post	Individual Response*
		$\bar{x}$ (SD)	$\bar{x}$ (SD)	Decrease/Trivial/Increase
Body mass (kg)	C	69.3 (7.16)	71.0 (7.09)	0/4/4
	WR	76.5 (4.60)	78.6 (4.62)	0/5/6
F_0 (N·kg^{-1})	C	6.60 (0.63)	6.14 (0.56)	6/1/1
	WR	6.83 (0.45)	5.98 (0.61)	10/0/1
P_{max} (W·kg^{-1})	C	13.4 (1.74)	12.9 (2.03)	4/2/2
	WR	14.1 (1.04)	12.9 (1.11)	7/2/2
V_0 (m·s^{-1})	C	8.17 (0.61)	8.47 (0.71)	1/0/7
	WR	8.29 (0.43)	8.69 (0.56)	1/1/9
S_{FV} (%)	C	-0.81 (0.09)	-0.73 (0.05)	1/0/7
	WR	-0.83 (0.08)	-0.69 (0.11)	1/0/10
D_{RF} (%·s·m^{-1})	C	-7.50 (0.78)	-6.72 (0.47)	1/0/7
	WR	-7.61 (0.71)	-6.41 (0.95)	1/0/10
RF_{max} (%)	C	46.7 (3.22)	46.3 (2.80)	4/2/2
	WR	48.3 (2.11)	45.7 (2.07)	8/1/2
5 m time (s)	C	1.41 (0.06)	1.47 (0.08)	1/1/6
	WR	1.39 (0.04)	1.49 (0.07)	1/0/10
10 m time (s)	C	2.23 (0.11)	2.28 (0.12)	2/2/4
	WR	2.19 (0.05)	2.30 (0.10)	1/1/9
20 m time (s)	C	3.63 (0.18)	3.67 (0.20)	2/2/4
	WR	3.56 (0.09)	3.66 (0.10)	1/3/7
30 m time (s)	C	4.87 (0.13)	4.95 (0.29)	3/1/3
	WR	4.85 (0.15)	4.92 (0.14)	2/1/7
V_{max} (m·s^{-1})	C	7.75 (0.51)	7.97 (0.58)	1/1/6
	WR	7.89 (0.35)	8.13 (0.40)	1/1/9

Note: * Individual training response identified as an increase or decrease from pre-intervention measure using smallest worthwhile change threshold (i.e. > ± 0.20 × pre-intervention between subject SD).

Figure 16. Pre- and post-intervention theoretical maximal horizontal force (F_0) and theoretical maximal velocity (V_0) for the athletes in the wearable resistance group (solid black line) and control group (dashed grey line)



Note: A filled in circle at post means the training response was greater than the smallest worthwhile change.

The results of the ANCOVA, used to determine differences between groups on post-intervention measures, are reported in Table 16. After adjustment for pre-intervention measures, small (non-significant, $p > 0.05$) effects were found for all variables except V_{max} (ES = 0.09).

Table 16. Adjusted mean difference scores for post-intervention measures with pre-intervention measures as a covariate with results of the one-way ANCOVA for between-group *p*-value and effect size statistics

	WR-Control		
	Mean Difference	***p*-value**	**ES**
F_0 (N·kg^{-1})	-0.21	0.48	0.35
P_{max} (W·kg^{-1})	-0.54	0.39	0.42
V_0 (m·s^{-1})	0.11	0.54	0.30
S_{FV} (%)	0.04	0.37	0.43
D_{RF} (%·s·m^{-1})	0.34	0.37	0.43
RF_{max} (%)	-0.91	0.45	0.37
5 m time (s)	0.03	0.40	0.41
10 m time (s)	0.04	0.36	0.44
20 m time (s)	0.04	0.42	0.40
30 m time (s)	0.06	0.39	0.44
V_{max} (m·s^{-1})	0.02	0.86	0.09

8.4 Discussion

This study determined the effects of a lower-limb WR sprint running training intervention incorporated into a nine-week off-season, low volume training period for American football high school athletes. Our hypothesis was unsupported as there were no statistically significant between group differences observed. However, there were other findings of practical significance worthy of discussion. The main findings were: 1) WR training used in this study did not produce significant improvements in sprint running time, velocity, or horizontal F-v mechanical variables as compared to unloaded training; and, 2) the sprint training programme produced increases in velocity measures beyond the SWC for the majority of athletes.

For a sprint training protocol to produce positive adaptations in performance, the protocol must include adequate recovery time, training frequency, and total training volume [91]. The detraining of several variables that occurred for athletes in both groups suggests that recovery time was inadequate or the training protocol failed to provide the minimum stimulus necessary to maintain or improve performance. Although the athletes in WR group did not experience significant improvement in sprint performance measures beyond changes seen in the control group, they did complete a greater off-season training workload by completing the same sprint training prescription with an external load. Additionally, this greater training workload was highly movement- and velocity-specific to the technical demands of the task. A factor that may have influenced the lack of transfer of the resistance training to sprint running performance was, in fact, this higher training workload experienced by the athletes in the WR group. We received feedback from the coaching staff mid-intervention that stated consistent identification of in-practice fatigue indicators for the WR group. In this instance, a decision was made to delay the progression of the WR location from proximal to mid by one week to week five, as reflected in the study timeline (Table 14). It may be that the inclusion of the WR during the corresponding warm-up sessions induced an accumulation of fatigue throughout the intervention, in which the athletes were unable to recover by post-intervention testing. An advantage of WR training is that the athlete can complete a relatively higher training load in the same amount of time but this must not come at a compromise to recovery. Additionally, no offloading or tapering period was used in this study. Short tapering time frames (e.g. 1–2 weeks) have been shown to maximise the training response of sprint running performance [52,64]. It is unknown if the response to the WR training peaked after the post-intervention test occurred.

In sprint running, the F-v relationship is used to identify an athlete's horizontal force production abilities from zero to theoretical maximal velocity and these abilities are represented by the F-v profile with the F_0 and V_0 values representing each end of the spectrum. While the optimal profile balance and relative magnitude of each component of the F-v relationship are currently unknown for sprint running [44,50], determining athletes' F-v profiles can be useful to identify individual mechanical capabilities relative to group norms, detect changes that occur over time, and understand adaptations to specific training stimuli. In this study, 16 of the 19 athletes across both groups experienced a positive training response in V_0 (quantified by the SWC threshold), indicating an improved ability to produce horizontal force at higher velocities. Considering the majority of athletes in both the WR and control group responded with positive V_0 changes, this suggests the training programme itself was successful in influencing the velocity end of the F-v spectrum.

In this study, it is possible that the WR training provided a superior velocity-oriented stimulus as compared with unloaded training, as greater adjusted mean V_0 scores ($p > 0.05$; ES = 0.30) from the ANCOVA were found for the WR group at post-intervention testing. This contrasts with findings of a previous study where the WR group did not experience a significant change in V_0 measures following the use of the same shank WR intervention over a six-week time frame while the control group that completed the same sprint training with no WR did [35]. In that instance, the training protocol utilised in Feser et al. [35] appears to have emphasised repeat sprint ability by including upwards of 22 repetitions in a single training session. This leads to the possibility that the WR group completed the large volume of sprint running at slower sprint speeds than their control group counterparts resulting in less of an influence in the velocity measures of interest. Instead, early acceleration specific measures (i.e. F_0 and RF_{max}) were positively influenced beyond that of the control group [35]. Taken together, it can be suggested that WR may amplify the nuances of particular sprint running training protocols. However, further understanding is needed to better determine how to optimise WR programming to complement the goals of training.

Faster sprint running acceleration is related to an athlete's ability to apply large forces to the ground, to orient the force vector in a more horizontal direction, and to maintain the horizontal force vector orientation with increasing speed [23,71,86]. An athlete's acceleration specific strength capacity and technical abilities can be quantified with the measures F_0, RF_{max}, and D_{RF}. The majority of the athletes in this study decreased F_0 (16 out of 19 athletes) and RF_{max} (12/19) and increased D_{RF} (17/19) following the sprint training and subsequently increased in sprint times as indicated by the number of training responses greater than the SWC thresholds (≥ 58.8% of all athletes). Although an increase to D_{RF} could be interpreted as a technical improvement, i.e. a less steep decline in ratio of force with increasing speed, the athletes simultaneously decreased RF_{max} and increased V_{max}. This global change to sprint performance impacted D_{RF} and, instead, suggest ratio of force was lower at almost all speeds post-intervention testing. This may be further evidence of how this training program influenced the F-v spectrum. It appears the improvements to the velocity end of the spectrum came at a cost to the force end of the spectrum for the majority of the athletes. It should also be noted that the between-group comparison of the adjusted post-intervention measures showed the WR group to have lower F_0 and RF_{max} values and higher DRF. Although the differences between the groups were small and not significant ($p > 0.05$; ES = 0.37–0.43), this reiterates the suggestion that WR amplifies the nuances of the training protocol itself.

Also, it is possible that the changes in F_0, D_{RF}, and RF_{max} and subsequent increase in sprint times for WR group athletes were related to the athletes' initial F_0 levels, per the hypothesis that an athlete's response to different sprint running training modalities may be contingent on their initial F-v profile [30,87]. This has been shown in professional rugby players, where it was reported that the magnitude and direction of the training response to two different sprint training modalities were related to the initial F-v properties of the individual athletes [52]. In our study, the athletes with higher initial F_0 values tended to experience larger decreases in F_0 at post-testing. Specifically, three of the four athletes with the highest initial F_0 values experienced the largest decreases in F_0 over the course of the study (each > –20.0%; Figure 16). If the response to the sprint training programme was directly influenced by the initial F_0 value, the training programme itself may have overshadowed any adaptation from the WR training at the force end of the F-v spectrum for the athletes with higher initial F_0 values. Previously, lower-limb WR training for sprint running has been shown to produce a positive adaptation or be related to maintaining F_0 even with initial values higher than that seen in this study (8.09 $N \cdot kg^{-1}$ and 7.50 $N \cdot kg^{-1}$, respectively) [35,57]. Future studies could consider randomising athletes into training groups based on performance metrics other than sprint times, such as F_0 level, to better control for differences in mechanical characteristics between individuals.

Research on the longitudinal effects of lower-limb WR training for short-distance sprint running is in its infancy. While its use as a training modality is well supported from a theoretical basis, continued investigation within practical athlete training settings is necessary for coaches and strength and conditioning practitioners to further understand how to optimise the benefits of WR training to influence athlete speed capabilities. Future research should consider how to best quantify the overload associated with WR training which may help inform programming decisions. This would lead to a better understanding of how the external workload prescription may need to be adjusted when using WR training (i.e. less sets and/or repetitions) compared to unloaded training. Until then, coaches and strength and conditioning practitioners can also consider employing alternative methods to adjust workloads during a WR training session such as reducing sprint distances, alternating between loaded and unloaded repetitions, or selecting particular drills to overload. This would still allow for an increased within-session workload to optimise strength and conditioning training goals within specific time periods while maintaining sensitivity to the pre-requisite individual- or group-based recovery times.

8.5 Practical Applications

As coaches and strength and conditioning practitioners look to find efficient and specific training modalities to increase sprint running speed, lower limb WR training holds logical potential to accomplish these needs. Given the results of previous shank loading WR training studies, it was expected that WR training would provide a training benefit over and above unloaded training. The WR training used in this study did not produce significant differences from unloaded training for sprint running time, velocity, or horizontal F-v mechanical variables. However, athletes in both the WR and control groups experienced increases in velocity measures, and the greater adjusted mean V_0 scores ($p > 0.05$; ES = 0.30) found for the WR group suggest that WR may suggest that WR amplify the nuances of the training protocol itself. However, it should be noted this increase to the velocity end of the F-v spectrum came at a cost to the force end of the F-v spectrum as lower F_0 and RF_{max} scores were found for the WR post-training. Coaches can consider using lower-limb WR training to increase in-session workloads during periods of low volume training but should be cognisant of the potential for fatigue accumulation due to the relatively higher training load inherent with WR training. Further research is needed to better understand how to programme WR training to influence individual athlete mechanical capabilities to improve sprint running performance.

Chapter 9. Summary, Limitations, Practical Applications, and Future Research

9.1 Summary

The purpose of this research was to answer the overarching question: “What are the effects of lower-limb WR on short distance sprint running?” This included investigating the underlying acute mechanical changes that occur with lower-limb WR and determining the effect of training with lower-limb WR on sprint running performance.

Sprint running, and in particular one’s ability to perform maximal acceleration over short distances, is a key component of performance for many sports. However, researchers had yet to well elucidate how resistance training can be used to improve sprint running performance. It was suggested that training with lower-limb WR may be a successful approach to producing adaptations that transfer to unloaded sprint running by circumventing the lack of movement speed- and pattern-specificity and loading limitations of the resistance training methods traditionally used for sprint running.

At the onset of this research, the knowledge on WR was limited and had yet to investigate many of the underlying acute mechanical changes that occur with lower-limb WR or the long-term effects of training with lower-limb WR in athletes (Chapter 2). Further investigation into the effects of two different WR placements would allow for better understanding to what underlying mechanical changes occur with lower-limb WR and if different load placements can be used to target certain aspects of sprint performance for training. Thus, research into the acute mechanical changes during sprint running with thigh and shank WR was undertaken. Motion capture analysis revealed that the joint angle changes during early sprint running acceleration with both 2% BM thigh and shank WR were small and $< 2°$ on average. The effect of WR loading had a greater influence on the angular velocity at the hip and knee joints (Chapter 3). The main findings from the investigation of the kinetic changes with 2% BM thigh and shank WR across 0–30 m (Chapter 4) was that athletes were largely able to maintain or increase horizontal force production values, such as theoretical maximal force, propulsive impulse, and net anterior-posterior impulse. Taken together, these studies highlight: 1) the velocity-specific nature of this resistance training method; 2) joint kinematics are less affected than kinetic outputs by the rotational inertia increase of shank-placed WR compared to the same load placed on the thigh; and, 3) what mechanical determinants are overloaded that over time may produce positive speed adaptations.

In Chapter 4, it was discovered that the alterations to horizontal braking and vertical impulse values were observed as early as 5 m with shank WR. This prompted a more detailed study (Chapter 5) into the ground reaction forces produced when sprint running with shank WR to better understand any underlying causes for increased impulse and determine if the addition of mass to the shank resulted in greater forces at impact. It was found that the overload provided to anterior-posterior force production with shank WR coincided closely with the performance demands at that stage of acceleration and thus holds potential as a targeted approach to improve sprint acceleration performance by challenging the transition between braking and propulsion. Additionally, horizontal braking and vertical forces were not increased during the impact phase of ground contact. This confirmed that practitioners can prescribe shank WR training with loads ≤ 2% BM for sprint running training with little concern such loading will increase the potential risk of injury that may be associated with greater forces during the impact phase.

On-field measures for the training studies included in this research were completed by the use of a radar gun. However, a technical investigation was also conducted to evaluate a 1080 Sprint device as a potential additional or substitute measurement option (Chapter 7). Specifically, we quantified and compared the magnitude of systematic bias and random error of horizontal F-v profile variables obtained from the 1080 Sprint and Stalker radar devices. The velocity data of 25% of the athletes measured were unable to be modelled by the exponential equation fitting process and, thus, rendered the 1080 Sprint not suitable for use within the following investigation (Chapter 8).

Two training studies were included in this research (Chapter 6 and 8). Both measured changes in sprint times, maximal velocity, and horizontal F-v profile variables and were implemented during an off-season training period in field-based sport athletes. Six weeks of WRT (Chapter 6) was found to superior to unloaded training in maintaining the technical ability to produce horizontal force at low velocities and maintaining a horizontally oriented ground reaction force with increasing speed in collegiate/semi-professional rugby athletes. These abilities would have otherwise detrained during the low-volume training period as observed in the control group. Nine weeks of WRT (Chapter 8) in high school American football athletes did not result in significant post-training differences between the WR and unloaded training. However, the majority of athletes in both training groups (WR and unloaded) responded with positive changes to V_0 scores, which suggests the training program itself was successful in influencing the velocity end of the F-v profile. Further, greater post-training V_0 scores ($p > 0.05$; ES = 0.30) were found for the WR group than the control group.

The differences in findings between the two training studies included in this research may be explained by looking at the sprint training protocols of each study as the progression of the 1% BM shank WR protocol was consistent between the two studies. In Chapter 6, the training protocol emphasised repeat sprint ability. This potentially resulted in the WR group completing the large volume of sprint running at slower sprint speeds than their control group counterparts, and thus, reducing the possibility of the WR to influence the velocity end of the F-v profile. In Chapter 8, the training included more explosive and maximal velocity-type drills, which coincided with greater changes to the measure representing performance at the velocity end of the F-v profile, V_0. Taken together, these studies provide evidence that shank-placed WR can be used to amplify the nuances of particular sprint running training protocols. However, further understanding is needed to better determine minimal worthwhile doses to help practitioners better understand how to optimise WR use within their training programmes.

9.2 Limitations

The limitations of this research are outlined here:

- The loading schemes used in Chapters 3 and 4 did not equate the magnitude of rotational overload between the two placement locations, and while it appears that shank-placed WR might uniquely affect some mechanical aspects of movement performance, this cannot be fully confirmed without first equating the rotational overload magnitude between thigh- and shank-placed WR.
- Only one thigh and shank WR loading scheme was used through Chapters 3–5, therefore, it is unknown how different load magnitudes and placements may alter joint kinematics, horizontal F-v profile variables, impulse, and stance phase ground reaction force production compared to the loading schemes used in this study.
- Joint kinematic measures were only quantified during early acceleration (Chapter 3), and thus, kinematics for the remaining portions of the acceleration phase have yet to be investigated.
- Other methods could be used to standardise the step comparisons seen in Chapters 4 and 5, such as a velocity-based comparison. Different comparison methods could render different results than what was observed in this research, which used a distance-matched comparison method.
- The kinetic analyses in Chapters 4 and 5 used linear measurement approaches to measure a rotational overload, which may be limiting in understanding the true nature of the imposed demands of lower-limb WR.
- Familiarisation sessions were provided in Chapters 3–5 but the athletes otherwise had no prior experience with WRT. Acute responses to sprint running with lower-limb WR may differ to that reported in these chapters following further familiarisation.
- The participants in Chapters 3–5 were sprint-based athletes, while the participants in Chapters 6 and 8 were field-based sports athletes, therefore, the acute effects identified in Chapters 3–5 may differ to what would have been seen with field-based sports athletes due to probable differences in sprinting expertise and physical characteristics, and vice versa.
- The systematic bias and random error between the horizontal F-v profile variables obtained from a 1080 Sprint to that obtained from a radar reported in this research are only applicable when the same processing approach is used, and therefore, it cannot be assumed all processing approaches will yield the same results.

- Due to limited access to measurement technology in Chapter 6 and 8, longitudinal step and joint kinematic adaptations to WRT were not reported in this research. Analysis of these measures would serve in understanding if the acute changes associated with lower-limb WR sprint running were a stimulus for specific adaptation.
- Due to limited training group sizes, in Chapter 6 and 8, a second intervention group was unable to be utilised, therefore a comparison of the longitudinal effects of thigh versus shank WR remains unknown.
- In Chapter 6 and 8, no offloading or tapering period was used, and thus, it is unknown if the response to the WRT peaked after the post-intervention test occurred.
- In Chapter 6 and 8, a body mass percentage-based WR prescription was used. Other methods could be effective to standardise WR prescriptions such as using a velocity decrement, and the effect of those methods remain unknown.
- In Chapter 6 and 8, the WR protocol progressively overloaded the athletes by maintaining load magnitude and moving load placement distally. There are other methods to provide a progressive overload with WR, such as maintaining load placement and increasing load magnitude. How different methods compare remains unknown.
- In Chapter 6, low attendance rates resulted in a lower training volume than what was prescribed to improve performance through the pre-season. It is unknown if an increase in performance would have occurred with the WRT beyond the unloaded training if the athletes attended all prescribed training sessions.
- In Chapter 8, inclement winter weather resulted in several cancellations of training sessions, which required alterations to the training protocol during the off-season period. It is unknown if improved performance would have occurred for either the WR or control groups if the athletes were able to complete the training protocol as initially prescribed.

9.3 Practical Applications

Upon considering the findings of this research, the following practical recommendations are provided:

- Lower-limb WR provides a rotational overload to the sprint running movement pattern.
- Lower-limb WR provides an overload through the entire swing phase and stance phase of sprint running, while other forms of resistance training (e.g. resisted sled towing or weighted vest) only provide a direct overload during stance.
- Lower-limb WR can be used to selectively overload stride/step frequency and contact times with maintenance of stride/step lengths.

In reference to sprint running with 2% BM WR placed on the thigh or shank, the following practical recommendations are provided:

- Increases to sprint times and decreases to sprint velocity will be minimal, preserving the velocity-specific nature of the resistance training method.
- Average changes to maximal hip and knee joint angles will be small (< 2°) during early acceleration, however, some athletes may have much larger changes. Specific coaching cues should be provided in cases where the changes are deemed undesirable with respect to the individual's training needs.
- Athletes will largely maintain or increase horizontal force production values in response to the loading.
- Lower-limb WR provides a unique stimulus to overload relative horizontal braking impulse during acceleration, especially when WR placement is located on the shank.
- A given WR load provides a different overload magnitude based on the movement speed of the athlete. Practitioners may choose heavier WR loads to provide a greater overload for initial acceleration-specific work and lighter WR loads to provide a comparable overload during higher velocity-specific work.
- Practitioners can prescribe shank WR training with loads ≤ 2% BM with little concern such loading will increase the forces incurred during the impact portion of ground contact.

In reference to sprint running training with a 1% BM shank WR placement, the following practical recommendations are provided:

- When training frequency is low, WR can be used to increase the workload of the training session.
- Although athletes experience a greater workload when adding WR to a sprint training programme, perceived exertion of the training session (i.e. RPE) may remain unchanged.
- Adaptations to general WR exposure will amplify the nuances of the training programme itself.
- Increases to workload with WR may result in fatigue accumulation and should not compromise recovery. Alternative methods can be used to adjust workloads during a WR training session to maintain sensitivity to pre-requisite individual- or group-based recovery times. These methods could include reducing sprint distances, alternating between loaded and unloaded repetitions, or selecting particular drills to overload.
- Lower-limb WRT does not wholly replace other resistance training methods. This method of resistance training should be used concurrently or sequentially with other resistance training methods (e.g. gym-based maximal strength training) based on the

development status of the athlete, sport-specific requirements, individual needs, and goals of the training cycle.

9.4 Future Research

The opportunities for future research on the use of lower-limb WR as a training method for sprint running performance are extensive. Some of the opportunities emerging from this research include:

- Comparing the acute responses of different thigh and shank WR load magnitudes.
- Determining optimal training prescription schemes. This research used a body mass percentage approach. Other approaches are possible, such as a velocity-decrement method.
- Investigating the necessary exposure to WRT needed to elicit sprint running performance improvements.
- Investigating the effect of lower-limb WR use during specific drills commonly used to influence specific aspects of sprint running performance. This will help determine if the limb-loading can be used to produce the desired outcomes faster and further inform individualised use of lower-limb WR programming.
- Determining how to best quantify the internal and external workload changes associated with different WR magnitudes and placements for applied scenarios.
- Further determining if specific variables related to sprinting expertise are positively influenced following WRT, such as thigh angular velocity.
- Evaluating how longitudinal exposure to specific lower-limb WR placements may be used as a tool for implicit learning.
- Determining how WR may be used to strengthen the hamstrings to promote injury prevention and performance related adaptations.

9.5 Conclusion

This thesis provided research aimed at evaluating the appropriateness of lower-limb WR as a training stimulus for sprint running performance and providing practical recommendations for programming WRT for sprint running. Considering the necessity of sprint running as a facet of athletic performance for many sports, the best methods to develop an athlete's sprint running capabilities is of interest to many coaches. Lower-limb WR is a movement- and speed-specific method of resistance training when used during sprint running and sprint running-related drills. This research has identified what mechanical determinants are overloaded by lower-limb WR, and thus, may be influenced overtime to produce positive speed adaptation. Although the volume or frequency of exposure needed to produce an increase in performance following the introduction of lower-limb WR to a training programme is still unknown, it is suggested that this method of resistance training could be used concurrently with other resistance training methods in a mixed-method training approach to provide a unique stimulus to encourage continued improvement in speed development or further target velocity-based individual weaknesses. Lower-limb WRT was also found to be a time-efficient method for sprint-specific training to avoid detraining, which may have interesting implications for sports with constrained schedules. Furthermore, moving forward researchers should endeavour to better understand how to programme WRT to target individual athlete mechanical capabilities to improve sprint running performance.

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Appendices

Appendix I. Chapter 3 Supplementary Material

Marker Set Descriptions

Prefixes R and L denote right and left side of body
Italic font denotes markers used during the calibration process and removed for dynamic trials
Regular font denotes markers in place for the entire duration of the data collection session

<u>Thigh Loading Condition:</u>
Pelvis, right/left
- Anterior superior iliac spine (RASI, LASI)
- Posterior superior iliac spine (RPSI, LPSI)
- Iliac crest (RILC, LILC)

Thigh, right/left
- *Standard thigh cluster (RTH1-4, LTHI-4) – calibration only*

Knee, right/left
- *Lateral Femoral condyle (RLFC, LLFC) – static calibration only*
- *Medial Femoral condyle (RMFC, LMFC) – static calibration only*

Tibia, right/left
- Custom proximal 4-mkr cluster (pRTB1-4, pLTB1-4)
- Custom distal 3-mkr cluster (RTB1-3, LTB1-3)

Ankle, right/left, medial/lateral
- *Lateral Malleolus (RLMAL, LLMAL) – static calibration only*
- *Medial Malleolus (RMMAL, LMMAL) – static calibration only*

Foot, right/left
- Head of Metatarsal 1 (RMT1, LMT1)
- Head of Metatarsal 5 (RMT5, LMT5)
- Calcaneus (RCAL, LCAL)

Trunk
- Mid-point of Clavicles (CLAV)
- Xiphoid Process (STRN)
- Spinous Process C7 Vertebra (C7)
- Spinous Process T10 Vertebra (T10)

Note: Images also depict locations of inertial sensors (with markers mounted upon them) on the sacrum, each thigh, and each tibia. These markers and inertial sensors were not used in the *research presented in this manuscript. The markers mounted on the wearable resistance itself weights (green-striped items at bottom of shorts) were also not used for this manuscript.*

<u>Shank Loading Condition:</u>

Pelvis
- Anterior superior iliac spine (RASI, LASI)
- Posterior superior iliac spine (RPSI, LPSI)
- Iliac crest (RILC, LILC)

Thigh
- Standard thigh cluster (RTH1-4, LTHI-4)

Knee
- *Lateral Femoral condyle (RLFC, LLFC) – static calibration only*
- *Medial Femoral condyle (RMFC, LMFC) – static calibration only*

Tibia
- *Standard 4-mkr cluster (RTB1-4, LTB1-4) – calibration only*
- Custom distal 3-mkr cluster (RTB1-3, LTB1-3)

Ankle
- *Lateral Malleolus (RLMAL, LLMAL) – static calibration only*
- *Medial Malleolus (RMMAL, LMMAL) – static calibration only*

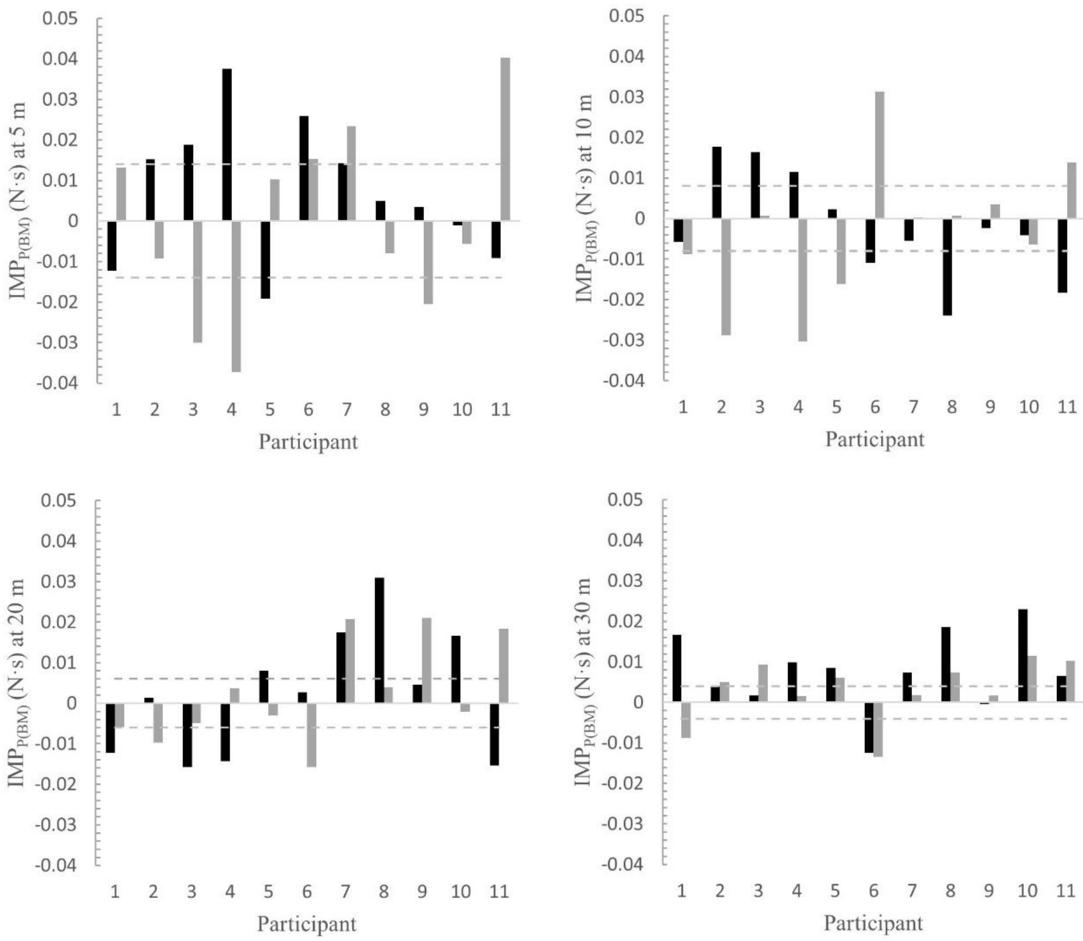
Foot
- Head of Metatarsal 1 (RMT1, LMT1)
- Head of Metatarsal 5 (RMT5, LMT5)
- Calcaneus (RCAL, LCAL)

Trunk
- Mid-point of Clavicles (CLAV)
- Xiphoid Process (STRN)
- Spinous Process C7 Vertebra (C7)
- Spinous Process T10 Vertebra (T10)

Note: Images also depict locations of inertial sensors (with markers mounted upon them) on the sacrum, each thigh, and each tibia. These markers and inertial sensors were not used in the research presented in this manuscript. The markers mounted on the wearable resistance itself (green-striped items at bottom of shorts) were also not used for this manuscript.

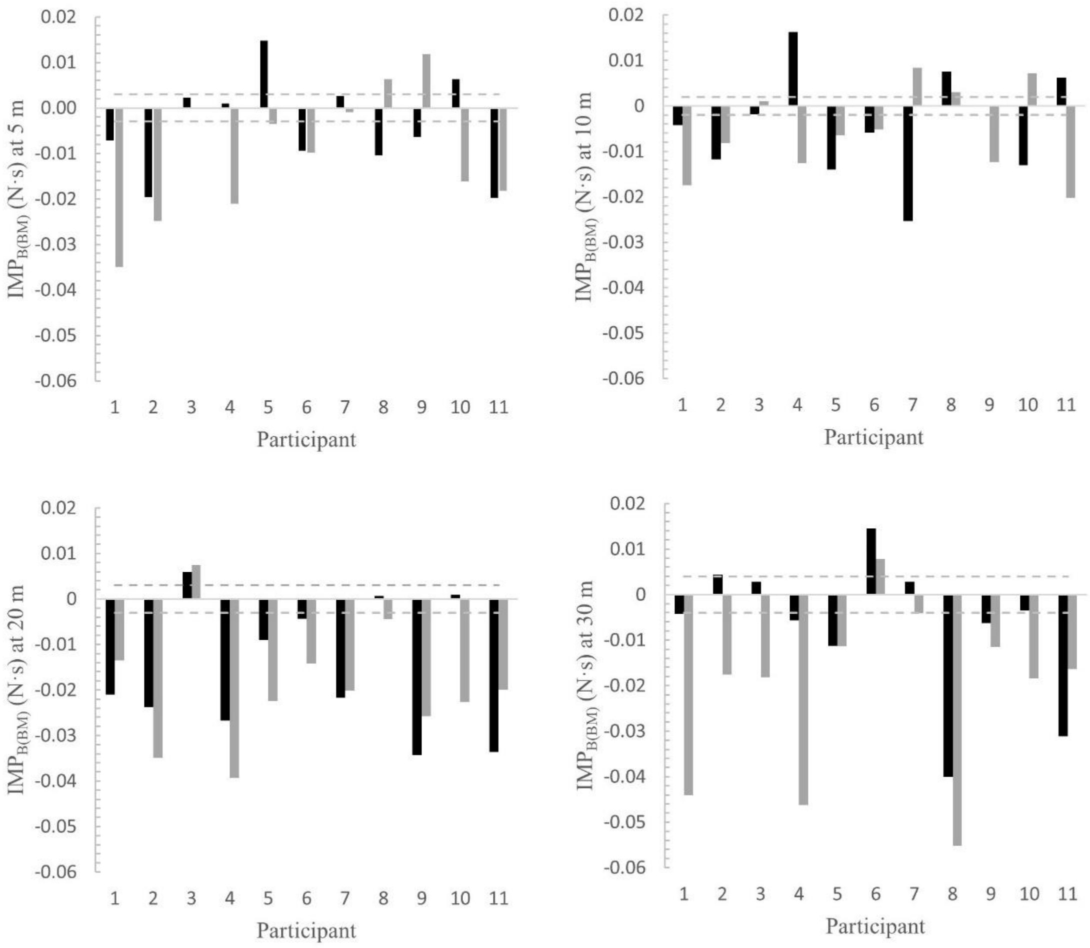
Appendix II. Chapter 4 Supplementary Material

Figure 17. Absolute change in propulsive impulse from the unloaded condition with thigh (black) and shank (grey) wearable resistance for each participant at each distance-matched step (5, 10, 20, and 30 m)



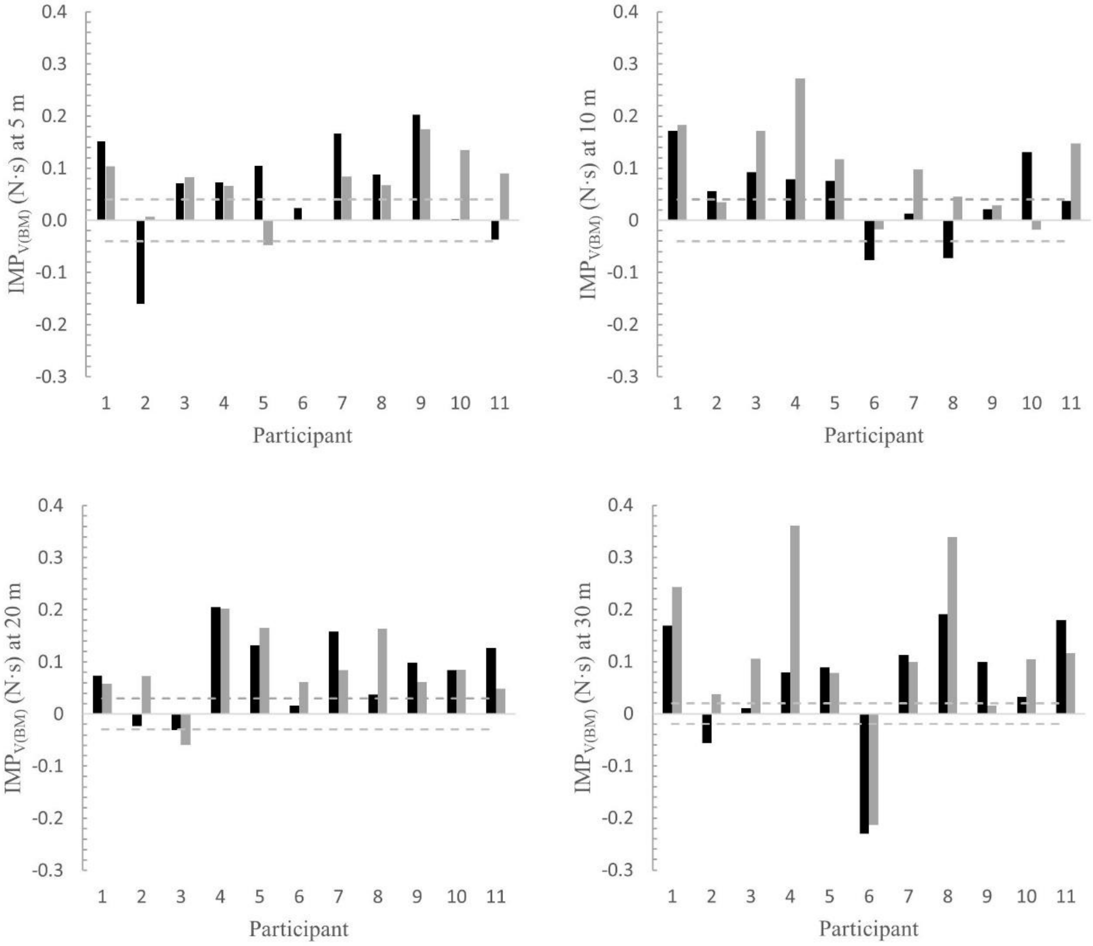
Note: Dashed lines indicate the smallest worthwhile change threshold (± 0.20 × unloaded condition between-subject standard deviation). IMP_P = propulsive impulse; IMP_B = braking impulse; IMP_V = vertical impulse.

Figure 18. Absolute change in braking impulse from the unloaded condition with thigh (black) and shank (grey) wearable resistance for each participant at each distance-matched step (5, 10, 20, and 30 m)



Note: Dashed lines indicate the smallest worthwhile change threshold (± 0.20 × unloaded condition between-subject standard deviation). IMP_P = propulsive impulse; IMP_B = braking impulse; IMP_V = vertical impulse.

Figure 19. Absolute change in vertical impulse from the unloaded condition with thigh (black) and shank (grey) wearable resistance for each participant at each distance-matched step (5, 10, 20, and 30 m)



Note: Dashed lines indicate the smallest worthwhile change threshold (± 0.20 × unloaded condition between-subject standard deviation). IMP_P = propulsive impulse; IMP_B = braking impulse; IMP_V = vertical impulse.

Appendix III. Ethical Approval

Listed here are the most recent approval documentation for:

- AUTEC Ethics Application Number 15/07 for data collection at the National Institute of Fitness, Kanoya, Japan (Chapters 3-5)
- ASU IRB Study Number 00007660 for data collection for Chapters 6-8
- AUTEC Ethics Application Number 19/318 for approval of research approved by an external ethics committee (i.e. Arizona State University [ASU])

AUTEC Secretariat

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20 February 2018

John Cronin
Faculty of Health and Environmental Sciences

Dear John

Re: Ethics Application: **15/07 Light variable resistance training with exogen exoskeletons.**

Thank you for your request for approval of an amendment to your ethics application.

The amendment to the recruitment protocols is approved.

I remind you of the Standard Conditions of Approval.

1. A progress report is due annually on the anniversary of the approval date, using form EA2, which is available online through http://www.aut.ac.nz/researchethics.
2. A final report is due at the expiration of the approval period, or, upon completion of project, using form EA3, which is available online through http://www.aut.ac.nz/researchethics.
3. Any amendments to the project must be approved by AUTEC prior to being implemented. Amendments can be requested using the EA2 form: http://www.aut.ac.nz/researchethics.
4. Any serious or unexpected adverse events must be reported to AUTEC Secretariat as a matter of priority.
5. Any unforeseen events that might affect continued ethical acceptability of the project should also be reported to the AUTEC Secretariat as a matter of priority.

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

AUTEC grants ethical approval only. If you require management approval for access for your research from another institution or organisation then you are responsible for obtaining it. If the research is undertaken outside New Zealand, you need to meet all locality legal and ethical obligations and requirements.

For any enquiries please contact ethics@aut.ac.nz

Yours sincerely,

Kate O'Connor
Executive Manager
Auckland University of Technology Ethics Committee

Cc: ksimperingham@gmail.com

ASU Knowledge Enterprise Development

APPROVAL: EXPEDITED REVIEW

Erin Feser
Exercise Science and Health Promotion
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Dear Erin Feser:

On 3/12/2018 the ASU IRB reviewed the following protocol:

Type of Review:	Initial Study
Title:	Changes in sprint-running performance and mechanical responses following a 5 week training period with lower-limb wearable resistance.
Investigator:	Erin Feser
IRB ID:	STUDY00007660
Category of review:	(6) Voice, video, digital, or image recordings, (4) Noninvasive procedures, (7)(a) Behavioral research
Funding:	Name: Global Sport Institute
Grant Title:	
Grant ID:	
Documents Reviewed:	• Limb load training PROTOCOL.docx, Category: IRB Protocol; • IRB Submission - external sites list.pdf, Category: Other (to reflect anything not captured above); • PAR-Q.pdf, Category: Screening forms; • Sport2036_EFeser.pdf, Category: Sponsor Attachment; • GSI Seed Grant Proposal - E.Feser 2017.pdf, Category: Sponsor Attachment; • Appendix B.pdf, Category: Technical materials/diagrams; • Appendix A - Recruitment script.pdf, Category: Recruitment Materials; • Appendix C - Consent.pdf, Category: Consent Form;

The IRB approved the protocol from 3/12/2018 to 3/11/2019 inclusive. Three weeks before 3/11/2019 you are to submit a completed Continuing Review application and required attachments to request continuing approval or closure.

If continuing review approval is not granted before the expiration date of 3/11/2019 approval of this protocol expires on that date. When consent is appropriate, you must use final, watermarked versions available under the "Documents" tab in ERA-IRB.

In conducting this protocol you are required to follow the requirements listed in the INVESTIGATOR MANUAL (HRP-103).

Sincerely,

IRB Administrator

cc:

Megna Mishra

Auckland University of Technology Ethics Committee (AUTEC)

Auckland University of Technology
D-88, Private Bag 92006, Auckland 1142, NZ
T: +64 9 921 9999 ext. 8316
E: ethics@aut.ac.nz
www.aut.ac.nz/researchethics

29 August 2019

John Cronin
Faculty of Health and Environmental Sciences

Dear John

Ethics Application: **19/318 Changes in sprint-running d and mechanical responses following a 5-week training period with lower-limb wearable resistance**

I wish to advise you that a subcommittee of the Auckland University of Technology Ethics Committee (AUTEC) has **approved** your ethics application.

This approval is for three years, expiring 27 August 2022.

Non-Standard Conditions of Approval

1. Update the Information Sheet/Consent Form removing Paul and add that Erin is the Doctoral student from AUT.

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

Standard Conditions of Approval

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

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

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

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

Yours sincerely,

K O'Connor

Kate O'Connor
Executive Manager
Auckland University of Technology Ethics Committee

Cc: erinfeser@asu.edu

Appendix IV. Participant Information Sheets, Pre-Participation Questionnaires, Consent Forms, and Assent Forms

Listed here are the documents associated with the data collection sessions at the National Institute of Fitness, Kanoya, Japan (Chapters 3-5), University of Pretoria, Pretoria, South Africa (Chapter 6), and Hinsdale High School, Hinsdale, USA (Chapters 7 and 8).

Participant Information Sheet

Date Information Sheet Produced:

18 October 2017

Project Title

Light Variable Resistance Training™ with Exogen™ Exoskeletons

An Invitation

My name is Paul Macadam and I am a PhD student at SPRINZ (Sports Performance Research Institute New Zealand) at the AUT Millennium Campus of the Auckland University of Technology (AUT). We are currently conducting a study into the effect on sporting movements of added external weight using a new product called an Exogen™ exoskeleton (*see photos below*). Your participation in this study would be greatly valued, but is entirely voluntary and you may withdraw at any time prior to the completion of the data collection.

Lila™, the producer of Exogen™, will provide Exogen™ suits for use during testing and may provide some grants (e.g. student scholarships) to help fund the research project. The results from the studies will be provided in de-identified form (i.e. without your associated name and personal details) to Lila™ in the form of journal or thesis publications and/or conference presentations. Your consent to participate in this research will be indicated by your signing and dating the consent form. Signing the consent form indicates that you have read and understood this information sheet, freely give your consent to participate, and that there has been no coercion or inducement to participate.

What is the purpose of this research?

The purpose of this research is to analyse the changes in typical sporting movements (e.g. jumping, running, sprinting and cycling) that occur when small amounts of external loading are attached to the body. Exogen™ exoskeletons include shorts, sleeveless tops and upper arm, forearm and calf sleeves to which small (approximately 19 cm long) loads of 50 – 200 g can be attached with Velcro. This research will

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quantify the acute changes in typical sporting movements that occur when loads are attached to various sites around the body (e.g. upper vs. lower body and centrally located loading vs. loading positioned towards the extremities of the limbs). The research findings will be reported as conference presentation(s) and scientific journal article(s).

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

Participants are required to be healthy, injury-free recreationally- or competitively-active males aged 18-40 years old. You have been identified by the National Institute of Fitness and Sports in Kanoya as a suitable participant for this project so we would like to invite you to participate.

What will happen in this research?

If you choose to participate in this project, you will be required to complete 2-4 testing session at National Institute of Fitness and Sports in Kanoya for approximately one to two hours per session.

Following the standardised 10-15 minute warm-up you will complete a series of 30 to 50 m over-ground sprints with and without Exogen loading attached to either the thigh, shank or forearm. Sprints will be performed with retro-reflective markers attached to torso and lower limbs (Figure 1) for lower limb loaded sprints. In addition, markers will be attached to the upper limbs (Figure 2) for upper limb loaded trials. Markers will also be placed on inertial measurement units (IMUs) attached via strapping to the back, thigh and shank, and the Exogen loads. Following the static and dynamic calibration trials the anatomical markers will be removed.

Figure 1. Attachment sites of retro-reflective markers and inertial measurement units with strapping for lower limb loading

Figure 2. Attachment sites of retro-reflective markers for upper limb loading

What are the discomforts and risks?

There should be no significant discomforts or risks associated with this testing beyond those experienced during normal sprint/strength testing and training. You will likely experience some shortness of breath and perhaps some lower body muscular soreness in the 48 hours after each testing session. When completing testing you will be asked to complete the running tasks with your shirt off to reduce the amount of clothing movement around the markers placed on your body. However, if you are uncomfortable with this, we will provide you with a tight fitting shirt to wear during testing.

How will these discomforts and risks be alleviated?

You will be requested to not complete any high-intensity training in the 24 hours prior to each testing session and to present to each testing session well hydrated and having not eaten in the 90 minutes prior to the start of testing. You will perform a comprehensive warm-up and cool-down before and after each testing session. Full recovery of at least three minutes will be ensured before each maximal effort test.

What are the benefits?

The research findings will inform and improve the effectiveness of athletic training procedures particularly in the areas of speed, power and endurance running training. As a participant you can receive a report of the research outcomes and your individual results at the completion of the study. These results can be used to individualise your on-going strength and conditioning program decisions. Additionally, if you are involved in an organised sport, a summary of your results can be made available to your team coach, manager or doctor if you agree to this on the consent form.

What compensation is available for injury or negligence?

In the unlikely event of a physical injury as a result of your participation in this study, the National Institute of Fitness and Sports in Kanoya will be the first point of contact to deal with any incidents.

How will my privacy be protected?

- We will take several measures to protect your privacy as much as possible and to ensure your personal details remain confidential.
- The data from the project will be coded and held confidentially in secure storage under the responsibility of the principal investigator of the study in accordance with the requirements of the New Zealand Privacy Act (1993).
- All reference to participants will be by code number only in terms of the research publications. Identification information will be stored on a separate file and computer from that containing the actual data.
- De-identified test results (i.e. without your associated name and personal details) may be stored indefinitely in the SPRINZ research database and may be used for similar research studies in the future.
- The findings of this project will be published in scientific journals, at a conference presentation(s) and in a doctoral thesis, but at no stage will you be identifiable. The results will be presented as averages and not individual responses. Your identifiable test results will only be made available to yourself and your sports coach, manager or doctor (if you agree to this option on the consent form).

What are the costs of participating in this research?

Participating in this research project will not cost you apart from your time, which we greatly thank you for. The total time commitment will be approximately 1-2 hours per session and depending on selection you will do 2-4 sessions.

What opportunity do I have to consider this invitation?

- Please take as much time as required to consider the invitation to participate in this research.
- It is reiterated that your participation in this research is completely voluntary.
- If you require further information about the research topic please feel free to contact Professor John Cronin (details are at the bottom of this information sheet).
- You may withdraw from the study at any time without there being any adverse consequences of any kind.
- You may ask for a copy of your results at any time and you have the option of requesting a report of the research outcomes at the completion of the study.

How do I agree to participate in this research?

If you agree to participate in this study, please complete and sign the attached consent form. This form will be collected in person prior to testing.

Will I receive feedback on the results of this research?

We will provide a summary via email of your results from the testing and the averages of all participants. If you wish to receive your results, please provide your email on the attached consent form where indicated.

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

Any concerns regarding the nature of this project should be notified in the first instance to the Project Supervisor, John Cronin, john.cronin@aut.ac.nz, 0064 921 9999 ext 7523.

Concerns regarding the conduct of the research should be notified to the Executive Secretary of AUTEC, Kate O'Connor, ethics@aut.ac.nz, 0064 921 9999 ext 6038.

Whom do I contact for further information about this research?

Researcher Contact Details:

Paul Macadam
Sports Performance Research Institute New Zealand (SPRINZ) at AUT Millennium, Auckland University of Technology, 17 Antares Place, Mairangi Bay, Auckland, New Zealand, 0632.
paul.maadam@gmail.com

Project Supervisor Contact Details:

Professor John Cronin
Sports Performance Research Institute New Zealand (SPRINZ) at AUT Millennium, Auckland University of Technology, 17 Antares Place, Mairangi Bay, Auckland, New Zealand, 0632.
john.cronin@aut.ac.nz
00 64 921 9999 ext 7523

Approved by the Auckland University of Technology Ethics Committee on 14 April 2015, AUTEC Reference number 15/07.

Consent Form

Project title:	**Light Variable Resistance Training™ with Exogen™ Exoskeletons**
Project Supervisor:	**Professor John Cronin**
Researcher:	**Paul Macadam**

- ○ I have read and understood the information provided about this research project in the Information Sheet dated 18 October 2017.
- ○ I have had an opportunity to ask questions and to have them answered.
- ○ I understand that I may withdraw myself or any information that I have provided for this project at any time prior to completion of data collection, without being disadvantaged in any way.
- ○ I am not suffering from heart disease, high blood pressure, any respiratory condition (mild asthma excluded), any illness or injury that impairs my physical performance.
- ○ I agree to take part in this research.
- ○ I agree that my test results may be provided to my sports coach, manager or doctor.

  Yes○ No○
- ○ I agree to my test results being stored in de-identified form (without my name or personal details attached) in the SPRINZ research database and potentially used in future research studies of a similar nature:

  Yes○ No○
- ○ I wish to receive a copy of the report from the research (please tick one):

  Yes○ No○

Participant's signature:

....

Participant's name:

....

Participant's Contact Details (if appropriate):

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Date:

Approved by the Auckland University of Technology Ethics Committee on 14 April 2015, AUTEC Reference number 15/07.

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Medical Questionnaire

Project title: **Light Variable Resistance Training™ with Exogen™ Exoskeletons**

Project Supervisor: **Professor John Cronin**

Researcher: **Paul Macadam**

First Name: ______________________________

Last Name: ______________________________

Email: ________________________________

Phone: ________________________________

Date of Birth: ____ / ____ / ______ *day / month / year*

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Do you currently have any form of muscle or joint injury? Y / N

If you answered **Yes**, please give details

____

____

____

Have you had any form of muscle or joint injury in the last six months? Y / N

If you answered **Yes**, please give details

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- ☐ I have read and understood the information provided about this research project in the Information Sheet dated 18 October 2017.
- ☐ I understand that I may withdraw myself or any information that I have provided for this project at any time prior to completion of data collection, without being disadvantaged in any way.
- ☐ I have answered the questions and provide the required information above to the best of my ability.
- ☐ I agree to take part in this research.

Participant's signature:...

Date: ....

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College of Health Solutions
Arizona State University

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Appendix C

CONSENT FORM

INTRODUCTION
The purposes of this form are to provide you (as a prospective research study participant) information that may affect your decision as to whether or not to participate in this research and to record the consent of those who agree to be involved in the study.

RESEARCHERS
Erin Feser, Adjunct Faculty in the College of Health Solutions, Arizona State University and Paul Macadam, doctoral student in Sport and Exercise, Auckland University of Technology has invited your participation in a research study.

STUDY PURPOSE
The purpose of the research is to measure the effects of lower-limb wearable (WR) on sprint-running performance following a 5-9 week training period with lower-limb WR of up to 2% body mass WR.

DESCRIPTION OF RESEARCH STUDY
If you decide to participate, then as a study participant, you will be asked to complete a minimum of 10 sprint training sessions within a 5-9 week time period. The duration is to be determined by what coincides with your current training regime. During each training session, estimated to last 1 hour or less, you will participate in a warm-up and a series of 7-10 sprints ranging between 20-50 meters. You may be randomly selected to complete the sprint training while wearing provided compression garments with up to 2% body mass attached at the thigh or calf. At the end of each practice session you will be asked, "how hard was this practice session" and your rating on a scale of 1-10 will be recorded. Prior to and following the training period you will be asked to participate in a series of data collection session estimated to last 30 minutes. These sessions will occur at a maximum of 3 times prior to the training period and 2 times following the training period. These sessions will consist of sprint running measurements. To collect the data needed for this study, small inertial sensors will be placed on your thighs, lower leg, and waist with elastic bands. The data collected for this study will consist of movement data recorded from sensors, video images, self-reported rating of perceived exertion, and anthropometric measurements. Prior to study participation you will be asked to complete a Physical Activity Readiness Questionnaire and report your training status and history to an investigator.

If you say YES, then your participation will last for the length of time that it takes you to complete a minimum of 10 sprint training sessions and 2 data collection sessions at your training facility. Approximately 20-30 participants will be participating in this study.

RISKS
The risks associated with this study are minimal and do not exceed the risks associated with sport and resistance training participation. The loading scheme utilized in this study is well below the typical loading used for resistance training protocols associated with sport training. Potential risks associated with the activities involved in this study include muscle fatigue and soreness. To further minimize injury risk, you will be required to wear appropriate shoes during the study, such as gym shoes or running shoes. You will be able to stop anytime to rest to minimize risks.

BENEFITS
The possible/main benefits of your participation in the research are contributing to the scientific knowledge base. You may also have your individual study results following all data collection procedures.

NEW INFORMATION
If the researchers find new information during the study that would reasonably change your decision about participating, then they will provide this information to you.

College of Health Solutions
Arizona State University

CONFIDENTIALITY

The results of this research study (including video footage or images) may be used in reports, presentations, and publications. In order to maintain confidentiality of your records, names would not be associated with data points, images or videos. All data collected will be detached from individual names and identified only by ID number. Data will be housed on password protected computers that only the main researchers will have access to. Data (including corresponding videos and images) will be kept for a period of 6 years, after which they will be deleted. Electronic data sharing of the two primary researchers will occur by a collaborative Dropbox folder that is only assessable by the two primary researchers.

WITHDRAWAL PRIVILEGE

It is ok for you to say no. Even if you say yes now, you are free to say no later, and withdraw from the study at any time.

Your decision will not affect your relationship with Arizona State University.

COSTS AND PAYMENTS

There is no payment for your participation in the study.

COMPENSATION FOR ILLNESS AND INJURY

If you agree to participate in the study, then your consent does not waive any of your legal rights. However, no funds have been set aside to compensate you in the event of injury.

VOLUNTARY CONSENT

Any questions you have concerning the research study or your participation in the study, before or after your consent will be answered by the Primary Investigator Erin Feser (erinfeser@asu.edu)

If you have questions about your rights as a subject/participant in this research, or if you feel you have been placed at risk, you can contact the Chair of the Human Subjects Institutional Review Board, through the ASU Office of Research Integrity and Assurance, at 480-965 6788.

This form explains the nature, demands, benefits and any risk of the project. By signing this form you agree knowingly to assume any risks involved. Remember, your participation is voluntary. You may choose not to participate or to withdraw your consent and discontinue participation at any time without penalty or loss of benefit. In signing this consent form, you are not waiving any legal claims, rights, or remedies. A copy of this consent form will be given (offered) to you.

Your signature below indicates that you consent to participate in the above study. Additionally, by signing below, you are granting to the researchers the right to use your likeness, image, appearance and performance - recorded on videotape or photographs - for presenting or publishing this research)

____________________ Subject's Signature	____________________ Printed Name	__________ Date
____________________ Other Signature (if appropriate)	____________________ Printed Name	__________ Date

INVESTIGATOR'S STATEMENT

"I certify that I have explained to the above individual the nature and purpose, the potential benefits and possible risks associated with participation in this research study, have answered any questions that have been raised, and have witnessed the above signature. These elements of Informed Consent conform to the Assurance given by Arizona State University to the Office for Human Research Protections to protect the rights of human subjects. I have provided (offered) the subject/participant a copy of this signed consent document."

Signature of Investigator____ Date______________

College of **Health Solutions**
Arizona State University

RESEARCH STUDY - Changes in sprint-running performance and mechanical responses following a 5-9 week training period with lower-limb wearable resistance.

PARENTAL LETTER OF PERMISSION

Dear Parent:

I am an Adjunct Faculty Member in the College of Health Solutions at Arizona State University. I am conducting a research study to measure the effects of lower-limb wearable (WR) on sprint-running performance following a 5-9 week training period with lower-limb WR of up to 2% body mass WR.

I am inviting your child's participation, which will involve attending and participating in practice as invited to by the team's coaching staff. Members of the research team will record practice procedures, record athlete participation, and collect sprint performance data. If you decide to allow your child to participate, then as a study participant, he/she will be asked to complete a minimum of 10 sprint training sessions within a 5-9 week time period, duration to coincide with current athlete training regime. During each training session, estimated to last 1 hour or less, he/she will participate in a warm-up and a series of 7-10 sprints ranging between 20-50 meters. Your child may be randomly selected to complete the sprint training while wearing provided compression garments with up to 2% body mass attached at the thigh or calf. Following each training session your child will be asked to rank on a scale of 1-10 "how hard was this practice session". Prior to and following the training period your child will be asked to participate in data collection sessions estimated to last 30 minutes. (Up to 3 sessions prior to the training period and 2 sessions following the training period.) These sessions will consist of sprint running measurements. To collect the data needed for this study, small inertial sensors will be placed on the thighs, lower leg, and waist with elastic bands. The data collected for this study will consist of movement data recorded from sensors, video images, self-reported perceived exertion ratings, and anthropometric measurements. Prior to study participation your child will be asked to complete a Physical Activity Readiness Questionnaire and report their training status and history to an investigator.

Your child's participation in this study is voluntary. If you choose not to have your child participate or to withdraw your child from the study at any time, there will be no penalty (it will not affect your child's involvement in team activities, interaction with the coaching staff, etc). Likewise, if your child chooses not to participate or to withdraw from the study at any time, there will be no penalty. The results of the research study may be published, but your child's name will not be used.

The risks associated with this study are minimal and do not exceed the risks associated with sport and resistance training participation. The loading scheme utilized in this study is well below the typical loading used for resistance training protocols associated with sport training. Potential risks associated with the activities involved in this study include muscle fatigue and soreness. To further minimize injury risk, your child will be required to wear appropriate shoes during the

550 North 3rd Street, Phoenix, AZ 85004
Phone: 602.496.2644 | Fax: 602.496.0886

study, such as gym shoes or running shoes. Your child will be able to stop anytime to rest to minimize risks.

Although there may be no direct benefit to your child, the possible benefit of your child's participation is increased understanding of sprint running performance characteristics. There are no foreseeable risks or discomforts to your child's participation above and beyond regular sport practice participation.

To protect confidentiality, all data will be collected and stored detached from individual names. The results of this study may be used in reports, presentations, or publications but your child's name will not be used.

If you have any questions concerning the research study or your child's participation in this study, please call me at (502) 595 - 7085.

Sincerely,

Erin Feser, MS
Adjunct Faculty
College of Health Solutions
Arizona State University

By signing below, you are giving consent for your child ___________________ (Child's name) to participate in the above study, be photographed and videotaped for data collection, and relinquish confidentiality in the event a video footage or image is used in a scientific report, presentation or publication.

_____________________ _____________________ _________
Signature Printed Name Date

If you have any questions about you or your child's rights as a subject/participant in this research, or if you feel you or your child have been placed at risk, you can contact the Chair of the Human Subjects Institutional Review Board, through the Office of Research Integrity and Assurance, at (480) 965-6788.

College of
Health Solutions
Arizona State University

RESEARCH STUDY - Changes in sprint-running performance and mechanical responses following a 5-9 week training period with lower-limb wearable resistance.

ASSENT FORM

My name is Erin Feser and I am a researcher at Arizona State University. I am conducting a research study to understand a new method of training for sprint running.

I am asking you to take part in a research study because I am trying to learn more about a new method of training for sprint running. I want to measure how effective the new method is. Your parent(s) has given you permission to participate in this study.

If you agree, you will be asked to attend and participate in practice as guided by your team's coaching staff. Members of my research team will record what you do at practice, how often you attend practice, how hard you thought practice was, and collect sprint performance data. You may be randomly selected to complete your sprint running training while using the new method of training. This new method of training involves attaching small amounts of weight to the legs with Velcro.

You do not have to be in this study. No one will be made at you if you decide not to do this study. Even if you start the study, you can stop later if you want. You may ask questions about the study at any time.

If you decide to be in study I will not share your individual data with anyone else. Even if your parents or coach asks, your individual data will not be publicized.

Signing here means that you have read this form, or have had it read to you, and that you are willing to be in this study.

Signature of subject: ____________________________________

Subject's printed name: ____________________________________

Signature of investigator: ____________________________________

Date: ______________

Appendix V. Chapter Abstracts

Chapter 2. The effects of lower limb wearable resistance on sprint running performance: a systematic review

The aim of this review was to examine the literature that has used lower limb wearable resistance (WR) during sprint running. A systematic search was completed to identify acute and longitudinal studies assessing the effects of lower limb WR on sprint running performance from international peer-reviewed journals. The Boolean phrases (limb OR leg OR lower extremity) AND (sprint*) AND (resist* OR weight OR load*) were used to search PubMed, SPORTDiscus, and Web of Science electronic databases. Ten studies met the inclusion criteria and were retained for analysis that reported the acute kinematic and kinetic effects (n = 8), acute performance effects (n=3), and longitudinal effects (n=1). Results showed that the WR micro-loading (0.6-5% body mass) significantly increased contact time (2.9-8.9%), decreased step frequency (-1.4 to -3.7%), and slowed total sprint times (0.6-7.4%). Unloaded sprinting immediately following sprints with lower limb WR resulted in no significant change to total sprinting times. One longitudinal training study did not find a significant effect on maximal sprinting speed for non-trained participants. It can be concluded that not all step kinematic variables are affected during sprinting with an added load up to 5% body mass. Therefore, coaches can use lower limb WR to selectively overload certain aspects of sprint running, in particular stride frequency. It also appears that lower limb WR overloads sprint movement velocity and may provide a stimulus to increase horizontal force output, therefore, it may be inferred that lower limb WR has the potential to elicit improved sprinting performance.

Chapter 3. Lower-limb wearable resistance overloads joint angular velocity during early acceleration sprint running

Lower-limb wearable resistance (WR) allows for targeted resistance-based training during sports-specific movement tasks. The purpose of this study was to determine the effect of two different WR placements (thigh and shank) on hip, knee, and ankle joint kinematics during the acceleration phase of sprint running. Eighteen male, university-level sprint specialists completed maximal effort sprints while unloaded and with 2% body mass thigh- or shank-placed WR. High speed motion capture was used to measure early acceleration joint kinematics. The main findings were: 1) increases to 10 m sprint times were small with thigh and shank WR (effect size [ES] = 0.24–0.33) but only significant with shank WR loading ($p = 0.02$); 2) significant differences in peak joint angles between the unloaded and loaded conditions were small (ES = 0.23–0.38), limited to the hip and knee joints, and < 2° on average; 3) aside from peak hip flexion angles, no clear trends were observed in individual difference scores between the loaded and unloaded conditions for peak joint angles; and, 4) thigh and shank WR produced similar reductions in average hip flexion and extension angular velocities, while thigh WR decreased average knee extension velocity and shank WR increased average knee flexion velocity compared with unloaded sprint running (all < ± 27°/s, ES = 0.22–0.70, $p < 0.05$). The significant overload to hip flexion and extension velocity with both thigh and shank-placed WR may be especially helpful to target the flexion and extension actions associated with fast sprint running.

Chapter 4. Changes to horizontal force-velocity and impulse measures during sprint running acceleration with thigh and shank wearable resistance

This study determined the effects of two wearable resistance (WR) placements (i.e. thigh and shank) on horizontal force-velocity and impulse measures during sprint running acceleration. Eleven male athletes performed 50 m sprints either unloaded or with WR of 2% body mass attached to the thigh or shank. In-ground force platforms were used to measure ground reaction forces and determine dependent variables of interest. The main findings were: 1) increases in sprint times and reductions in maximum velocity were trivial to small when using thigh WR (0.00–1.93%) and small to moderate with shank WR (1.56–3.33%); 2) athletes maintained or significantly increased horizontal force-velocity mechanical variables with WR (effect size = 0.32–1.23), except for theoretical maximal velocity with thigh WR, and peak power, theoretical maximal velocity and maximal ratio of force with shank WR; 3) greater increases to braking and vertical impulses were observed with shank WR (2.72–26.3% compared to unloaded) than with thigh WR (2.17–12.1% compared to unloaded) when considering the entire acceleration phase; and, 4) no clear trends were observed in many of the individual responses. These findings highlight the velocity-specific nature of this resistance training method and provide insight into what mechanical components are overloaded by lower-limb WR.

Chapter 5. Waveform analysis of shank loaded wearable resistance during sprint running acceleration

Lower-limb wearable resistance (WR) provides a specific and targeted overload to the musculature involved in sprint running, however, it is unknown if greater impact forces occur with the additional limb mass. This study compared the contact times and ground reaction force waveforms between sprint running with no load and 2% body mass (BM) shank-positioned WR over 30 m. Fifteen male university-level sprint specialists completed two maximum effort sprints with each condition in a randomised order. Sprint running with shank WR resulted in trivial changes to contact times at 5 m, 10 m, and 20 m (effect size [ES] = < 0.20, $p > 0.05$) and a small, significant increase to contact time at 30 m by 1.94% (ES = 0.25, $p = 0.03$). Significant differences in ground reaction force between unloaded and shank loaded sprint running were limited to the anterior-posterior direction and occurred between 20.8–28.3% of ground contact at 10 m, 20 m, and 30 m. Shank WR did not result in greater magnitudes of horizontal or vertical forces during the initial impact portion of ground contact. Practitioners can prescribe shank WR training with loads ≤ 2% BM without concern for increased risk of injurious impact forces.

Chapter 6. Wearable resistance sprint running is superior to training with no load for retaining performance in pre-season training

This study determined the effects of a six-week lower-limb wearable resistance training (WRT) intervention on sprint running time, velocity, and horizontal force-velocity mechanical variables. Twenty-two athletes completed pre- and post-intervention testing of three maximal effort 30 m sprints. A radar device was used to measure sprint running velocity from which horizontal force-velocity mechanical profiling variables were calculated. All athletes completed two dedicated sprint training sessions a week for six-weeks during pre-season. The intervention (wearable resistance, WR) group completed the sessions with 1% body mass load attached to the shank, whilst the Control group completed the same sessions unloaded. For the Control group, all variables were found to detrain significantly ($p < 0.05$) over the training period with large detraining effects (ES > 0.80) for theoretical maximal horizontal force, slope of the force-velocity profile, maximal ratio of force, index of force application, 5 m and 10 m times. For the WR group, there were no significant changes to any recorded variables (all $p > 0.05$) and all effects of training were trivial or small (ES < 0.50). After adjustment for baseline differences, significant between group differences were found for all variables (moderate to large effects, ES > 0.58) except theoretical maximal velocity, 30 m time, and maximal velocity. The addition of light wearable resistance to sprint training during a six-week pre-season block enables the maintenance of sprint performance and mechanical output qualities that otherwise would detrain due to inadequate training frequencies.

Chapter 7. Comparison of the 1080 Sprint to radar for obtaining horizontal force-velocity profile variables during sprint running

This study established the magnitude of systematic bias and random error of horizontal force-velocity (F-v) profile variables obtained from a 1080 Sprint to that obtained from a Stalker ATS II radar device. Twenty athletes from an American football training group completed a 30 m sprint while the two devices simultaneously measured velocity-time data. The velocity-time data were modelled by an exponential equation fitting process and then used to calculate individual linear F-v profiles and related variables. The velocity data recorded with the 1080 Sprint for five athletes were unable to be modelled and removed from the final analysis. The devices were compared by determining the bias and random error, and the 95% limits of agreement. For the remaining 15 athletes, all bias values were within a 6.36% difference between the devices. A positive bias, indicating a higher measurement by the 1080 Sprint, was found for all variables except theoretical maximal horizontal force and peak power. These results provide practitioners with the information necessary to determine if the agreement between the devices is acceptable within the context of their specific application.

Chapter 8. The effects of lower-limb wearable resistance on sprint performance in high school American football athletes: a nine-week training study

Time constraints often result in the challenge to fit desired programming into training time allotments. Wearable resistance (WR) may be an option to optimise constrained training time. The purpose of this study was to determine the effects of a lower-limb WR sprint running training intervention on athlete speed capabilities following a nine-week off-season, low volume training period for American football high school athletes. Nineteen athletes completed pre- and post-intervention testing of two maximal effort 30 m sprints. Horizontal force-velocity mechanical profiling variables, sprint times, and maximal velocity were calculated from sprint running velocity data collected by a radar device. The athletes completed seventeen dedicated sprint training sessions during the off-season. The intervention (WR) group completed the sessions with 1% body mass load attached to the shanks (i.e. 0.50% body mass load on each limb). The control group completed the same training sessions unloaded. Post-intervention, no statistically significant between group differences were observed ($p > 0.05$). However, athletes in both groups experienced increases in velocity measures following the sprint training. The greater adjusted mean theoretical maximal velocity scores ($p > 0.05$; ES = 0.30) found for the WR group at post-intervention may suggest that WR amplifies the nuances of the training protocol itself. Coaches can consider using lower-limb WR training to increase in-session workloads during periods of low volume training but more research is needed to better understand how to optimise programming with wearable resistance training to improve sprint running performance.

Appendix VI. Additional Research Outputs

The following are peer-reviewed journal publications completed adjunct to the research of this thesis:

Macadam P, Mishra M, **Feser EH**, Uthoff AM, Cronin JB, Nagahara R, Tinwala F. Force-velocity profile changes with forearm wearable resistance during standing start sprinting. *Eur J Sports Sci*. 2020;20(7):915-919.

Macadam P, Cronin J, **Feser E**. Acute and longitudinal effects of weighted vests on sprint-running performance: a systematic review [published online ahead of print, 2019 May 9]. *Sports Biomech*. 2019;1-16. doi: 10.1080/14763141.2019.1607542.

Macadam P, Uthoff A, **Feser E**, Cronin J. The effects of different wearable resistance placements on sprint-running performance: a review and practical applications. *Strength Cond J*. 2019;41(3):79-96.

Cronin J, Dolcetti J, Macadam P, **Feser E**. Wearable resistance training for speed and agility. *Strength Cond J*. 2019;41(4):105-111.

Macadam P, **Feser EH**. Examination of gluteus maximus electromyographic excitation associated with dynamic hip extension during body weight exercise: A systematic review. *Int J Sport Phys Ther*. 2019;14(1):14-31.