ENHANCING SPRINT PERFORMANCE IN TEAM SPORT ATHLETES

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ABSTRACT

Effective methods of monitoring and training sprint-running performance for team sport athletes are important for optimising physical preparation for a range of sports. Wearable resistance (WR) training involves attaching external load to the body during physical activity. Recent advances in WR technology have enabled efficient loading methods also of the lower body. The overarching research question of this thesis was “Can WR training enhance sprint-running performance?” The aim of the research was to develop WR speed training guidelines for team sport athletes, based on an understanding of the acute and chronic biomechanical and performance changes that occur with speed training with lower body WR. The objective of Section 1 was to review and assess sprint profiling technologies that can reliably provide insights into some of the kinematic and kinetic determinants of sprint performance. Radar-derived and non-motorised treadmill-derived speed variables typically had acceptable reliability when the average of two sprint trials were analysed. Section 2 involved reviewing two inter-related sprint training methods: lower body WR training and the acute performance enhancement (APE) effects of ballistic exercises on subsequent sprint performance. Potential benefits of the methods and research gaps were identified, which became the focus of subsequent chapters. Section 3 consisted of four cross-sectional studies evaluating the acute biomechanical and sprint performance impacts of lower body WR loading. Early acceleration phase sprint times (≤ 10 m) were not significantly affected by WR up to 5% body mass (BM), but the percentage decrement in maximum velocity phase sprint velocity was approximately equivalent to the magnitude of the lower body loading relative to participant BM (i.e. 3-5%). During both the acceleration phase and the maximum velocity phase lower body WR (3-5% BM) resulted in significantly increased ground contact time (4-6%) and decreased step frequency (-2 to -3%). Wearing moderate (3% BM) WR was associated with increased functional theoretical maximum horizontal ground reaction force (GRF) at the start of acceleration, while heavy (5% BM) WR resulted in significantly lower (-4%) effective vertical GRF during acceleration and lower effective horizontal GRF and power (-5 to -8%) during the maximum velocity phase. There was some evidence that loading a dynamic warm-up or a series of sprints with lower body WR was more effective at achieving APE of sprint acceleration performance compared to loaded jumps. The final section of the thesis included a six-week training study. Similar small improvements in sprint performance (1-3%) and hip strength (3-11%) in the control and WR intervention groups meant that there was no evidence of additional benefit to training with lower body WR compared to traditional speed training. A range of limitations of the training study were discussed. Practical applications covered in the final chapter included: that lower body WR up to 5% BM provides a specific sprint training overload to the mechanical determinants of sprint performance; different loading recommendations were made for the acceleration phase, the maximum velocity phase and for the APE of subsequent unloaded sprint performance. Further training studies are required to determine if longitudinal benefits exist for WR training compared to traditional speed training.

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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 extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning."

Kim David Simperingham

Co-Authored Works

Chapter 2. Simperingham, K. D., Cronin, J. B. & Ross, A. (2016). Advances in sprint-running acceleration profiling for field-based team sport athletes: utility, reliability, validity and limitations. *Sports Medicine, 46*(11), 1619-1645.	KS 80% JC 12% AR 8%
Chapter 3. Simperingham, K. D., Cronin, J. B., Pearson, S. N. & Ross, A. (2019). Reliability of horizontal force-velocity-power profiling during short sprint-running accelerations using radar technology. *Sports Biomechanics, 18*(1), 88-99.	KS 80% JC 10% SP 5% AR 5%
Chapter 4. Simperingham, K. D., Cronin, J. B., Ross, A., Compton, A. & Brown, S. (2019). Reliability of short sprint-running accelerations assessed on a non-motorised treadmill. *Sports Biomechanics, [In review].*	KS 80% JC 5% AR 3% AC 7% SB 5%
Chapter 6. Simperingham, K. D., Macadam, P., Cronin, J. B. & Ross, A. (2019). Acute effects of loaded and unloaded ballistic exercise on sprint-running performance: a systematic review. *European Journal of Sport Science [In preparation].*	KS 80% PM 10% JC 5% AR 5%
Chapter 7. Simperingham, K. D. & Cronin, J. B. (2014). Changes in sprint kinematics and kinetics with upper body loading and lower body loading using Exogen exoskeletons: a pilot study. *Journal of Australian Strength and Conditioning,* 22(5), 69-72.	KS 90% JC 10%
Chapter 8. Simperingham, K. D., Cronin, J. B., Ross, A., Brown, S. R., Macadam, P. & Pearson, S. (2019). Changes in acceleration phase biomechanics during over-ground and treadmill sprinting with lower body wearable resistance. *Sports Biomechanics, [In review].*	KS 80% JC 5% AR 3% SB 5% PM 3% SP 4%
Chapter 9. Simperingham, K. D., Cronin, J. B., Ross, A., Brown, S. R., Macadam, P. & Pearson, S. (2019). Changes in maximum velocity phase biomechanics during over-ground and treadmill sprinting with lower body wearable resistance. *Sports Biomechanics, [In review].*	KS 80% JC 5% AR 4% SB 5% PM 2% SP 4%
Chapter 10. Simperingham, K. D., Cronin, J. B., Pearson, S. & Ross, A. (2015). Acute changes in sprint-running performance following ballistic exercise with added lower body loading. *Journal of Australian Strength and Conditioning,* 23(6), 86-89.	KS 85% JC 5% SP 5% AR 5%
Chapter 11. Simperingham, K. D., Cronin, J. B., Ross, A., Brown, S. R. & Macadam, P. (2019). Changes in sprint-running performance following six weeks of lower body wearable resistance training. *European Journal of Sport Science, [In preparation].*	KS 80% JC 5% AR 5% SB 5% PM 5%

We, the undersigned, hereby agree to the percentages of contribution to the chapters identified above and agree to the inclusion of the joint work in this thesis:

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ABBREVIATIONS

1RM	One repetition maximum
α	Angular acceleration
ω	Angular velocity
Af	Frontal area
APE	Acute performance enhancement
AW	Added weight
BM	Body mass
CI	Confidence interval
CMJ	Countermovement jump
CT	Contact time
CV	Coefficient of variation
Δy	Vertical displacement of the centre of mass
DJ	Drop jump
D_{RF}	Index of force application technique
Effective	Relative to system mass (body mass plus added wearable resistance)
F	Female
F0	Theoretical maximum horizontal ground reaction force
F_{air}	Aerodynamic friction force
F_h	Horizontal ground reaction force
Fmax	Estimation of maximum vertical ground reaction force
FT	Flight time
F_{tot}	Total/resultant ground reaction force

Functional	Relative to body mass
F_v	Vertical ground reaction force
G	Gear ratio
GRF	Ground reaction force
I	Moment of inertia
ICC	Intraclass correlation coefficient
IL	Inertial load (cycle ergometer)
kvert	Vertical stiffness
LoA	Limits of agreement
M	Male
MP	Mean horizontal peak power output
NMT	Non-motorised treadmill
NR	Not reported
PAP	Post-activation potentiation
PE	Physical education
Pmax	Maximum power output (radar-derived)
PP	Peak power output (treadmill-derived)
PP_{IL}	Peak power output (IL cycle-derived)
r	Correlation coefficient
$_{rel}$	Relative to body mass
RF	Ratio of forces
rLoA	Ratio limits of agreement
RSI	Reactive strength index

SD	Standard deviation
SEM	Standard error of measurement
SF	Step frequency
S_{Fv}	Slope of the force-velocity profile
SL	Step length
s_{max}	Maximum velocity (radar data)
T_I	Instantaneous torque
TEM	Technical error of measurement
UL	Unloaded
V0	Theoretical maximum vertical ground reaction force
vmax	Maximum velocity
WAnT	Wingate anaerobic test
WR	Wearable resistance
yo	Years old

CHAPTER 1

INTRODUCTION

Rationale of the Thesis

Field-based team sports such as rugby, soccer, American football and Australian Rules are typically characterised by frequent short (10-20 m or 2-3 s) acceleration sprints, with occasional longer (> 20 m) efforts depending on the sport and playing position (Gabbett, 2012; Johnston, Watsford, Austin, Pine, & Spurrs, 2016; Ross, Gill, & Cronin, 2015; Spencer, Bishop, Dawson, & Goodman, 2005; Tierney, Young, Clarke, & Duncan, 2016; Vigne, Gaudino, Rogowski, Alloatti, & Hautier, 2010; Ward, Ramsden, Coutts, Hulton, & Drust, 2018; Whitehead, Till, Weaving, & Jones, 2018). Team sport athletes targeting improvements in sprint performance can gain numerous learnings from sprinters (Mann, 2011; Morin et al., 2012; Nagahara, Naito, Morin, & Zushi, 2014; Rabita et al., 2015), however it should be noted that there are substantial differences between the two groups (Colyer, Nagahara, Takai, & Salo, 2018; Wild, Bezodis, North, & Bezodis, 2018). Effective, accurate and relevant methods of training and testing sprint-running performance are therefore important for both field-based team sport athletes (referred to as "team sport athletes" for the remainder of the thesis) and performance coaches.

Sprint performance is often quantified by the time to cover a short distance using photoelectric cells (Cronin & Templeton, 2008; Duthie, Pyne, Ross, Livingstone, & Hooper, 2006; Kawamori, Newton, Hori, & Nosaka, 2013), and may be combined with generic measures of vertical strength (e.g. back squat) and vertical power (e.g. countermovement jump) to monitor and compare athletic profiles (Lockie, Murphy, Knight, & Janse de Jonge, 2011; Morin, Jimenez-Reyes, Brughelli, & Samozino, 2019). But for sprint profiling to have useful diagnostic value it is important that the results also provide valid and reliable insight into some of the determinants of sprinting performance in order to inform subsequent individual-specific speed training approaches (Mendez-Villanueva & Buchheit, 2013; Morin & Samozino, 2016).

The acceleration phase and the maximum velocity phase of sprinting are biomechanically distinct (Mann, 2011; Nagahara, Kanehisa, Matsuo, & Fukunaga, 2019; Nagahara et al., 2014; von Lieres Und Wilkau, Irwin, Bezodis, Simpson, & Bezodis, 2018; Yu et al., 2016) and therefore require different training and testing approaches (Blazevich & Jenkins, 2002; Bolger, Lyons, Harrison, & Kenny, 2015; Lloyd, Radnor, De Ste Croix, Cronin, & Oliver, 2016; Lockie, Murphy, Schultz, Knight, & Janse De Jonge, 2012; Rumpf, Lockie, Cronin, & Jalilvand, 2016). The acceleration phase involves a body position with substantial forward lean in order to direct the ground reaction force (GRF) in a horizontal direction as much as possible (Hunter, Marshall, & McNair, 2005; Kawamori, Nosaka, & Newton, 2013; Kugler & Janshen, 2010; Rabita et al., 2015). The colloquial meaning of "acceleration" will be used in this thesis to refer to short (≤ 20 m) sprint performance and/or the section of positive horizontal acceleration in a sprint (Kawamori, Nosaka, et al., 2013). Faster acceleration phase speeds are achieved through longer ground contact time or a more posterior foot plant and therefore greater forward lean of the body (Kugler & Janshen, 2010). In contrast, the maximum velocity phase involves a more upright body position, where improved performance is associated with shorter ground contact time, longer step length and higher vertical stiffness (Bret, Rahmani, Dufour, Messonnier, & Lacour, 2002; Chelly & Denis, 2001; Kugler & Janshen, 2010; Mann, 2011; Nagahara & Zushi, 2017). The importance of the horizontal compared relative to the vertical component of the GRF in achieving faster running speeds during the maximum velocity phase is the source of ongoing debate (Brughelli, Cronin, & Chaouachi, 2011; Morin et al., 2012; Nagahara et al., 2019; Nummela, Keranen, & Mikkelsson, 2007; Weyand, Sternlight, Bellizzi, & Wright, 2000).

Advanced sprint profiling options that quantify some of the important mechanical determinants of sprint performance (e.g. horizontal GRF) include radar and laser devices as well as non-motorised and torque treadmills. Although the reliability and validity of these devices have been established during constant pace running (Brughelli et al., 2011; Chelly & Denis, 2001; Harrison, Jensen, & Donoghue, 2005; Lakomy, 1987; McKenna & Riches, 2007; Weyand et al., 2000), the methodological suitability for accurately assessing short, maximal-effort sprints remains to be determined.

Improved sprint performance can be achieved through improved physiological capabilities (e.g. increased force production or movement velocity capabilities of the limbs) (Lockie, Murphy, Callaghan, & Jeffriess, 2014; Lockie et al., 2012; Ross, Leveritt, & Riek, 2001) or improved technical capabilities (e.g. more horizontally oriented GRF outputs or altered kinematic step characteristics) (Kugler & Janshen, 2010; Mann, 2011; Rabita et al., 2015). Improving generic strength may assist in improving sprint performance (Bolger et al., 2015; Cronin, Ogden, Lawton, & Brughelli, 2007; Griffiths et al., 2019; Marques et al., 2015), however more specific training techniques (e.g. plyometrics and resisted/assisted sprinting) could be more effective for individuals with a higher training age, or those with an identified focus of improving the high velocity portion of the force-velocity curve (Macadam, Cronin, & Simperingham, 2017; Rumpf et al., 2016).

Wearable resistance (WR) training involves attaching external load directly to the body during sporting movements and has been incorporated into physical training programs for decades (Bosco, 1985; Bosco, Rusko, & Hirvonen, 1986; Ropret, Kukolj, Ugarkovic, Matavulj, & Jaric, 1998). Encouraging upper body WR training outcomes included acutely increased leg stiffness and running economy after a series of loaded stride outs (Barnes, Hopkins, McGuigan, & Kilding, 2015), and significantly improved vertical jump performance after three weeks of training (Bosco, 1985; Bosco et al., 1986). Recent advances in WR technology (e.g. the Lila™ Exogen™ compression-based suit) mean that small increments of weight can now easily be attached to or removed from the torso or limbs during sport-specific training sessions (Macadam, Cronin, et al., 2017). Increasing rotational inertia by adding external loads to the lower body instead of the upper body during sprinting mean that smaller magnitudes of WR are likely to have a significant impact on sprint biomechanics (Dolcetti, Cronin, Macadam, & Feser, 2018; Ropret et al., 1998). The flexibility afforded by newer WR technologies mean that not only the magnitude of loading, but also the placement (e.g. targeted body part, anterior vs posterior, proximal vs distal positioning) should be considered and periodised over time. However, at this point in time, the physiological and mechanical understanding associated with altering WR load and placement, to enhance sprint performance is rudimentary at best. A thorough understanding of the acute and chronic impact of lower body WR on sprint performance will inform subsequent training guidelines for team sport athletes, and as such provides the focus of this thesis.

Research Question and Objectives

The overarching research question of this thesis was: "Can WR training enhance sprint-running performance?". The aim of the research was to develop WR speed training guidelines for team sport athletes, based on an understanding of the acute and chronic biomechanical and performance changes that occur with speed training with lower body WR. To achieve this aim, the research objectives were:

1. Determine valid, reliable and practically useful methods of quantifying sprint-running performance (Section 1: Chapter 2, 3, 4).

2. Review lower body WR training literature and the effect of loaded and unloaded ballistic exercise on subsequent sprint performance (Section 2: Chapter 5, 6).

3. Evaluate the acute biomechanical and sprint performance impact of lower body WR training (Section 3: Chapter 7, 8, 9, 10).

4. Evaluate the chronic biomechanical and sprint performance impact of six weeks of lower body WR training (Section 4: Chapter 11).

Thesis Structure

This thesis was conducted using quantitative research methodology to answer the overarching research question and comprises a series of chapters each written in the format of a published scientific journal article. As such, repetition of some information (e.g. research methods and some points of discussion) inevitably occurs. Following this Introduction chapter (Chapter 1), the remaining 11 chapters are divided into four thematic sections outlined in Figure 1.

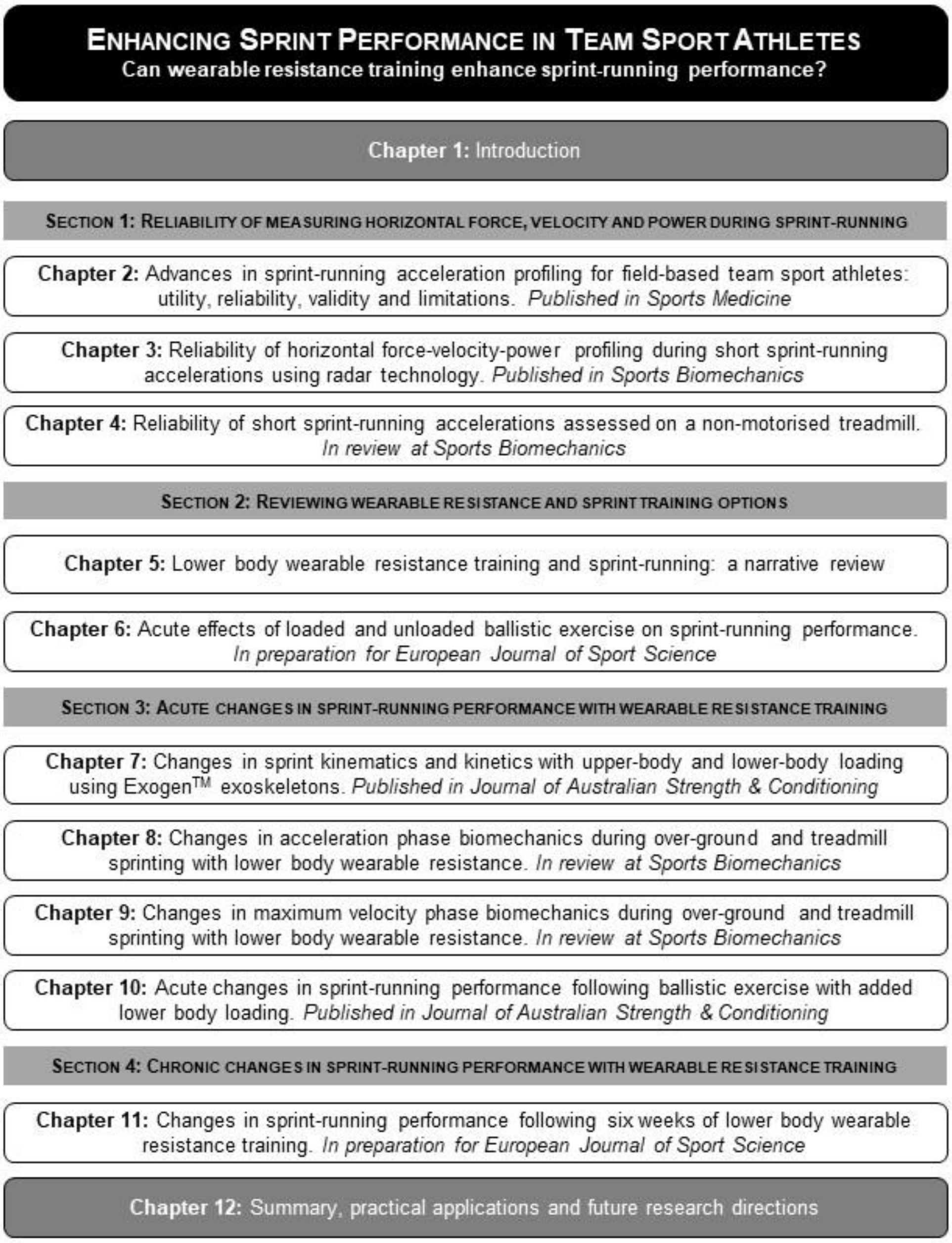

Figure 1. Thesis Structure.

Chapters 3-11 each begin with a Prelude that briefly describes the findings of the previous chapter and explains how the direction taken in the subsequent chapter will build upon these findings. The Prelude links the successive chapters together to ensure that the thesis is a cohesive whole.

Section 1 begins with a systematic review of the advanced speed testing options of radar, laser, non-motorised treadmill (NMT) and torque treadmill (Chapter 2). Utility, reliability, validity and limitations of each testing technology are summarised based on the available literature. Gaps in the literature that are identified in Chapter 2 are addressed with two speed profiling reliability studies: firstly, with a radar device (Chapter 3) and then with a NMT (Chapter 4). These reliability studies involve assessing the practical reliability of the testing and help determine the technology and protocols that will be implemented in ensuing chapters.

Section 2 includes two literature reviews. Firstly, a narrative review summarising the current knowledge about lower body WR and sprint-running (Chapter 5), and secondly a systematic review of research addressing the potential for ballistic exercise to acutely enhance subsequent sprint performance (Chapter 6). Both literature reviews in this section identify specific areas of limited knowledge about the effects of WR, which are addressed in the subsequent section of cross-sectional studies. Chapter 6 also generates useful speed training recommendations that are applied in the training study in the final section of the thesis.

Section 3 involves a series of four cross-sectional studies expanding the body of knowledge about the acute impact of sprinting with lower body WR. The differential effects of WR attached to the upper body compared to the lower body are quantified during treadmill sprinting (Chapter 7), and the effects of lower body WR during over-ground acceleration phase sprinting (Chapter 8) and maximum velocity phase sprinting (Chapter 9) are detailed in separate chapters. A single subject research design is used in the final chapter of this section to pilot the potential for a range of lower body loaded ballistic exercises to acutely enhance subsequent sprint performance (Chapter 10).

The final section of the thesis involves a comparison of a six-week speed training program with or without lower body WR. The speed training program for the group of team sport athletes is informed by the findings of Chapters 6-10 and the speed testing methods used throughout sections 3 and 4 are informed by the findings of Section 1 (Chapters 2-4). Finally, WR speed training guidelines for team sport athletes are proposed based on the findings throughout the thesis (Chapter 12).

SECTION 1

RELIABILITY OF MEASURING HORIZONTAL FORCE, VELOCITY AND POWER DURING SPRINT-RUNNING

Chapter 2

Advances in Sprint-Running Acceleration Profiling for Field-Based Team Sport Athletes: Utility, Reliability, Validity and Limitations

This chapter comprises the following paper published in *Sports Medicine:*

Simperingham, K. D., Cronin, J. B. & Ross, A. (2016). Advances in sprint-running acceleration profiling for field-based team sport athletes: utility, reliability, validity and limitations. *Sports Medicine, 46*(11), 1619-1645.

Introduction

Sprint-running speed is a critical success factor for field-based team sport athletes. However, considering that maximal velocity is rarely achieved (Lindsay, Draper, Lewis, Gieseg, & Gill, 2015; Vigne et al., 2010), speed testing for team sport athletes should concentrate on acceleration over the first 20 m rather than the maximal velocity phase. This contention is reinforced by researchers who, using time-motion analyses, have indicated the relative importance of short 10-20 m or 2-3 s accelerations rather than long maximal speed sprints during field-based team sports (Gabbett, 2012; Spencer et al., 2005; Vigne et al., 2010). Maximum speed capability is important for certain positional roles, but of critical importance for team sport strength and conditioning coaches and sport scientists is how best to assess sprint acceleration ability up to 20 m in order to meaningfully influence training program design.

The conventional meaning of the word "acceleration" will be used for the remainder of this review to refer to maximal effort short (≤ 10 s) sprint-running bouts with an increasing running speed (Kawamori, Nosaka, et al., 2013). Acceleration ability in team sports is commonly measured using photoelectric cells (or timing gates) to provide a time to cover a set distance (usually 5-20 m) (Kawamori, Newton, et al., 2013). While the reliability of photoelectric cell technology is well established (Cronin & Templeton, 2008; Grant M. Duthie et al., 2006), the measured split times provide little insight into the relative strength or weakness of the biomechanical or technical variables that may influence the result, and could be targeted in subsequent training programs. Mendez-Villanueva and Buchheit (2013) argued that sport-specific 5 m and 10 m sprint results tend to reinforce what coaches already know from observation, rather than provide any useful information about the factors responsible for the performance.

Some researchers of maximum velocity sprinting have suggested that the magnitude of the vertical component of the GRF (F_v) is most important (Weyand et al., 2000), while other researchers have concluded that the horizontal component of the GRF (F_h) is most important in achieving faster top running speeds (Brughelli et al., 2011; Morin et al., 2012; Nummela et al., 2007). Researchers of acceleration however, have consistently concluded that the horizontal orientation of the GRF is most critical during this phase of the sprint (di Prampero, Botter, &

Osgnach, 2015; Hunter et al., 2005; Kawamori, Nosaka, et al., 2013; Kugler & Janshen, 2010; Rabita et al., 2015). In fact Hunter et al. (2005) suggested that all strength reserves should be applied horizontally, except a magnitude of relative vertical impulse that enables a flight time just sufficient for the lower limbs to be repositioned. Additionally, Rabita et al. (Rabita et al., 2015) analysed 40 m sprints over in-ground force platforms and showed that elite sprinters produced higher F_h, but no difference in total GRF compared to sub-elite sprinters. In order for sprint acceleration profiling to be of true diagnostic value it is important that the results provide valid and reliable insight into some of the kinematic and kinetic determinants of sprinting performance. Of particular importance is quantification of the magnitude of F_h during the acceleration phase.

Advanced diagnostic tools that can be readily used to inform sprint training to better effect are: radar and laser devices, NMT and TT. Radar systems, such as the Stalker ATS System™ (Radar Sales, Minneapolis, MN, US), emit very high frequency radio waves and can then measure the change in frequency as the radio waves bounce off the sprinting subject. The reflected radio wave signals are converted into a stream of digital data and processed with software to provide the forward running speed of the subject at a typical sampling frequency of 35-100 Hz (Gander et al., 1994; Morin, Jeannin, Chevallier, & Belli, 2006). Laser systems, such as the Universal Laser Sensor (ULS, Laser Technology Inc, Centennial, CO, USA), use coherent light and measure the time delay of pulsed infrared light that is reflected off the subject. Compared to radar, laser emits a very narrow cone of light and can achieve sampling rates as high as 4000 Hz (Debaere, Jonkers, & Delecluse, 2013). The high radar and laser sampling rates result in instantaneous velocity data that enables the calculation of displacement, acceleration, F_h and power output (di Prampero et al., 2005; Morin & Seve, 2011; Samozino et al., 2015).

The NMT was first developed by Lakomy (1987) to provide a means to measure instantaneous power output during sprinting, analogous to power measurements during short, high-intensity efforts on a cycle ergometer. Conventional motorised treadmills are not suitable for sprint-running assessment due to the resulting kinematic changes compared to sprinting over-ground (Frishberg, 1983; McKenna & Riches, 2007). For example sprinting on a conventional treadmill results in a more extended knee at foot strike, faster hip extension velocity and longer ground contact and braking times (McKenna & Riches, 2007). The NMT enables the measurement of instantaneous changes in speed during sprinting as the subject drives the belt speed of the treadmill. The belt speed is typically monitored by optical speed photomicrosensors that are mounted in the rear shaft of the belt. The more modern NMT ergometers (e.g. Woodway Force, Eugene, OR, USA) provide a measure of F_v through load cells that are mounted under the belt surface (Brughelli, Cronin, Mendiguchia, Kinsella, & Nosaka, 2010). Rather than measuring F_h directly from the belt surface, measurement is instead achieved by applying Newton's Third Law of Motion. Subjects wear a harness around their waist with a tether attached to a horizontal load cell, which is attached to a vertical strut directly behind the NMT running surface (Figure 2). An alternate design involves subjects sprinting while gripping the treadmill handlebar equipped with a load cell (Yanagiya, Kanehisa, Kouzaki, Kawakami, & Fukunaga, 2003). Assuming the subject does not move relative to the belt surface, then the F_h that the subject applies to the ground equals the F_h measured at the load cell. Horizontal power output can then be calculated as the product of F_h and running speed.

Figure 2. Example of a NMT set-up including horizontal tether and load cell behind the subject.

TT are similar to NMT, however they are powered by a torque motor, which accounts for the subject's body weight and theoretically better mimics over-ground sprinting and assists subjects to achieve a more valid maximal sprinting speed (Chelly & Denis, 2001; Morin, Samozino, Bonnefoy, Edouard, & Belli, 2010). Morin et al. (2010) positioned the torque setting at a level that just enabled the belt to move when the subject was standing on the treadmill. The most advanced torque treadmill ergometers now enable the direct measurement of both F_v and F_h at the same location – the point of foot contact on the treadmill belt surface (Morin et al., 2010). NMT and torque treadmill sampling rates are generally between 10 and 1000 Hz. Commercially available and custom-made software programs can be used to analyse NMT and torque treadmill data. Additional kinematic and kinetic variables can be calculated, such as distance, speed, acceleration, power output, ground contact time, stride length, stride rate and the magnitude of the resultant GRF (F_{tot}; for those treadmills that enable measurement of horizontal braking GRF and horizontal propulsive GRF) (Brughelli et al., 2011; Lakomy, 1987; Morin et al., 2010).

The reliability and validity has been addressed for the assessment of constant pace running using radar (Chelly & Denis, 2001), laser (Harrison et al., 2005), NMT (Brughelli et al., 2011; Lakomy, 1987) and torque treadmill (McKenna & Riches, 2007; Weyand et al., 2000). However, the performance of these tools when assessing the acceleration phase is the most important consideration for athletes from sprint-based team sports. Therefore, the aim of this systematic review was to determine the utility, reliability, validity and limitations of (a) radar and laser technology and (b) NMT and torque treadmill technology for providing kinematic and kinetic measures of sprint acceleration performance. It was hypothesised that each of these advanced diagnostic tools would have acceptable reliability and validity for assessing sprint accelerations.

Methods

Search Criteria and Identification of Studies

A comprehensive search of five electronic databases (CINAHL Plus, MEDLINE (EBSCO), PubMed, SPORTDiscus and Web of Science) from inception to February 2015 was performed. The same databases were searched in November 2015 to identify more recent articles of relevance. Database results were limited to human studies, academic journals, reviews, and dissertations when applicable. The Web of Science database results were limited to the categories of sport sciences and physiology. Keywords were arranged into the following Boolean phrase: ([“non motor* treadmill" OR "torque treadmill" OR "instrumented treadmill" OR "sprint treadmill" OR radar OR laser] AND [sprint* OR acceleration OR speed OR run*] AND [kine* OR force OR power]). The search was not limited by language of publication. Inter-library loan facilities were used when the articles were not available through the institutional library.

Studies examining the kinematics or kinetics of short (≤ 10 s), maximal effort sprint acceleration in adults or children, which included an assessment of reliability or validity of the advanced technologies of interest (i.e. radar, laser, NMT and TT) were included. Studies of children were included in the search even though it is acknowledged that there may be differences in sprinting patterns between children and adults (Malina, Eisenmann, Cumming, Ribeiro, & Aroso, 2004; Rumpf, Cronin, Oliver, & Hughes, 2013). Valid and reliable sprint acceleration profiling was deemed to be important for both adolescent and adult athletes. Studies examining longer (> 10 s) or constant pace sprints, non-sprint based exercise (e.g. throws and jogging), injured or diseased populations, a split belt treadmill, or including no reliability or validity data of advanced technology were excluded. The reference lists of identified articles were hand searched. No study quality assessment was completed given that the focus of the review was on the reliability and validity results, rather than necessarily the overall outcomes of each study.

Study Selection

The study selection process involved removing duplicates, followed by screening for relevance on title, then abstract. The final step involved screening the full text articles using the inclusion/exclusion criteria.

Data Extraction and Analysis

Absolute reliability, relative reliability and validity data were extracted from the selected articles and summarised in tables for radar, laser, NMT and torque treadmill technology. Absolute reliability data included coefficient of variation (CV), standard error of measurement (SEM), limits of agreement (LoA) and ratio limits of agreement (RLoA). Relative reliability was quantified with intraclass correlation coefficient (ICC) or correlation coefficient (r) (including Pearson product moment correlation coefficient and Spearman's rho) (Atkinson & Nevill, 1998;

Hopkins, 2000). The level of acceptance for reliability was a CV ≤ 10% (Atkinson & Nevill, 1998; Hopkins, 2000) and an ICC or r ≥ 0.70 (Nunnally, 1978; Streiner & Norman, 2008; Vincent, 2005). Some additional validity results that were not included in the tables were instead explained in the Results section.

Results

Search Results and Study Characteristics

The original search of five electronic databases netted 1020 articles (Figure 3). Ten additional articles were identified via hand searches of article reference lists and databases. Following the removal of duplicates and screening for relevance on title and abstract, 79 full-text articles were screened for eligibility. Thirty-four studies met the inclusion criteria and were included in the qualitative synthesis.

The study characteristics of the 34 articles included in the review are summarised in Table 1. Populations sampled in the studies included untrained subjects; healthy, active subjects (including physical education students); and varying levels of athletes from team sports or track and field. At least six studies met the inclusion criteria for each of the testing technologies. Three studies were included in both the radar section and the torque treadmill section (Chelly & Denis, 2001; Morin, Edouard, & Samozino, 2011; Morin & Seve, 2011).

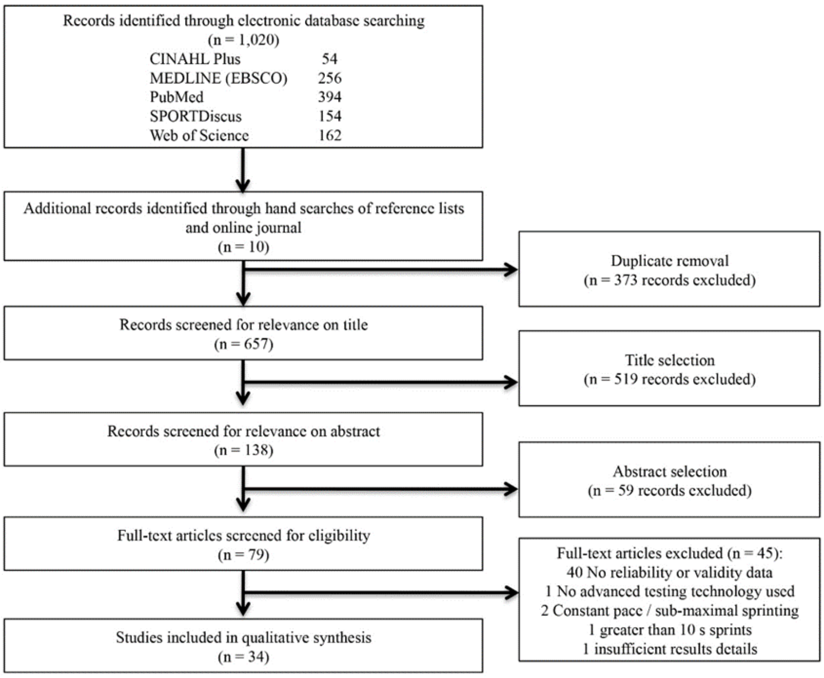

Figure 3. Search results and identification of studies through the different stages of the systematic review.

Radar and Laser Technology

Utility in Speed Profiling

The radar or laser device is typically positioned on a tripod set at a vertical height of 1 m to approximately align with the subject's centre of mass (COM) and placed directly behind the subject at a distance of 10 m (di Prampero et al., 2005; Morin et al., 2011; Morin et al., 2006; Morin & Seve, 2011) or 20 m (Bezodis, Salo, & Trewartha, 2012). However some studies use a shorter distance (e.g. 2.9 m) (Ferro, Floría, Villacieros, & Aguado-Gómez, 2012) or otherwise do not report the distance from the subject (Buchheit et al., 2014; Chelly & Denis, 2001; Debaere et al., 2013; Delecluse, Roelants, Diels, Koninckx, & Verschueren, 2005). The radar gun works on the Doppler principle so if subjects do not run directly towards or away from the device then an angle error will result in measured speeds that are lower than the actual speed (StalkerRadar, 2010). A 15 ° angle error will result in a 3.4% error in the recorded speed; if the radar is positioned closer than 10 m behind the subject in the start position, the likelihood of an angle error may be increased (StalkerRadar, 2010).

Table 1. Study characteristics of the 34 articles included in the review.

Reference	Device (model)	Sampling rate (Hz)	Intra-day reliability	Inter-day reliability	Validity	Sample	Study description
(Gander et al., 1994)	Radar (Gunnplexer)	100	No	No	Yes	n = 1 Experienced sprinter	Nine repeated sprints over a range of distances 10-30 m Comparison of radar and video data
(Gander et al., 1994)	Radar (Gunnplexer)	100	No	No	Yes	n = 5 Experienced sprinters	10 x 20 m Comparison of radar and photocell data
(Chelly & Denis, 2001)	Radar (Stalker ATS system)	NR	No	No	Yes	n = 11 Male handball players	Measured moving subjects (1-7 m/s) and rolling balls (8-22 m/s) over a 3 m section Comparison of radar and photocell data
(di Prampero et al., 2005)	Radar (Stalker ATS system)	35	Yes	No	Yes	n = 12 Male medium level sprinters	100 m sprint Comparison of radar and photocell data
(Morin et al., 2006)	Radar (Stalker ATS system)	35	No	No	Yes	n = 8 Male PE students	4 x 100 m sprints Comparison of radar and photocell data
(Morin & Seve, 2011)	Radar (Stalker ATS system)	35	No	No	Yes	n = 11 Male PE students	100 m sprint Comparison of actual and modelled speed data Comparison of F_h measured with radar and during a 100 m sprint on a TT
(Morin et al., 2011)	Radar (Stalker ATS system)	35	No	No	Yes	n = 12 Male PE students	100 m sprint Comparison of radar data and an 8 s sprint on an instrumented treadmill
(Samozino et al., 2015)	Radar (Stalker ATS system)	47	Yes	No	Yes	n = 6 High level sprinters	3 x 50 m sprints Comparison of two best trials (reliability) Comparison of best sprint (radar) with sprint data from imbedded force platforms (validity)
(Berthoin, Dupont, Mary, & Gerbeaux, 2001)	Laser (IBEO100)	2	No	No	Yes	n = 22 Male PE students	2x 100 m sprints Comparison between laser and photocells at 0, 20, 50, 100 m
(Delecluse et al., 2005)	Laser (IBEO Lasertechnik)	NR	Yes	No	No	n = 20 (13 M, 7 F) Experienced sprinters	2x 30 m sprints out of starting blocks
(Bezodis et al., 2012)	Laser (Jenoptik LDM-300C)	100	No	No	Yes	n = 10 (7 M, 3 F) Sprinters	50 m sprints Comparison of estimates of velocity from a laser and from the criterion of high-speed video at 1, 5, 10, 30 and 50m
(Debaere et al., 2013)	Laser (Universal Laser Sensor)	307.7	Yes	No	No	n = 20 (10 M, 10 F) High level sprinters	2x 60 m sprints
(Lakomy, 1987)	NMT (Woodway A/B)	> 20	Yes	No	No	n = 10 (5 M, 5 F)	1x 10 s sprint from standing start [a] Relationship between force, power and speed analysed
(Ferro et al., 2012)	LDM301 (Jenoptik)	2000	Yes	Yes	Yes	n = 17 (17 M)	3 x 30 m completed on two separate days Laser measurements compared to video and photocells

Reference	Device (model)	Sampling rate (Hz)	Intra-day reliability	Inter-day reliability	Validity	Sample	Study description
(Buchheit et al., 2014)	Laveg 300 C (Jenoptik)	100	Yes	No	No	n = 86 Elite academy soccer players	2 x 40 m sprints
(Tong, Bell, Ball, & Winter, 2001)	NMT (Woodway A/B)	100	Yes	Yes	No	n = 27 Male rugby players	3x 6 s sprints from a rolling start. 2 min between repeats. 1 week between sessions.
(Yanagiya et al., 2003)	NMT (Custom built model)	200	No	Yes	No	n = 8 Adult, males (Pilot study)	10x 5 s maximal sprints 10 s between efforts
(Yanagiya, Kanehisa, Tachi, Kuno, & Fukunaga, 2004)	NMT (Custom built model)	200	No	Yes	No	n = 15 (7 M, 8 F) (Pilot study)	2x ~7 s maximal sprints (standing start)
(Hughes, Doherty, Tong, Reilly, & Cable, 2006)	NMT (Woodway A/B)	10	No	Yes	No	n = 10 Male, healthy, active	6x 6s sprints 30s between efforts; repeated 3 times (within a week)
(Oliver, Williams, & Armstrong, 2006)	NMT (Woodway Tramp)	100	No	Yes	No	n = 12 Boys (avg 15.3 yo) Soccer/rugby players	7x 5 s sprint, rolling start (from 8 km/h) 20 s between efforts; 5 testing sessions; at least 1 day between sessions
(Sirotic & Coutts, 2008)	NMT (Woodway Force)	10	No	Yes	No	n = 11 Male, moderately trained team sport athletes	3x 3s sprints and 3x 6s sprints 2 min between sprints; testing completed 3 times, 5 days apart
(Hopker, Coleman, Wiles, & Galbraith, 2009)	NMT (Woodway Force 3.0)	100	No	Yes	Yes	n = 38 (21 M, 17 F) Team sport athletes of mixed ability	20 m sprint from rolling start Compared to 20 m sprint from a rolling start using photoelectric cells (validity)
(Sweeney, Wright, Brice, & Doberstein, 2010)	NMT (Woodway Force)	50	Yes	No	No	n = 19 Physically active, college men	2 sets of 5x 5s sprints with 45 s recovery, 2 min active recovery between sets (NMT resistance set at 15% of body mass)
(Serpiello, McKenna, Stepto, Bishop, & Aughey, 2011)	NMT (Woodway Force)	50	Yes	No	No	n = 10 (7 M, 3 F) Healthy, young adults	3 sets of 5x 4s sprints 20 s passive rest between efforts; standing start (but trial begins when 1 m/s velocity reached)
(Highton, Lamb, Twist, & Nicholas, 2012)	NMT (Woodway Force 3.0)	100	Yes	Yes	Yes	n = 12 Team sport athletes (non-elite)	3x 30 m sprint, stationary start 2 min between efforts; 24-48 hrs between sessions Compared to 3x 30 m over-ground sprint using photoelectric cells (validity)
(Nédélec, Berthoin, & Dupont, 2012)	NMT (Woodway Force 3.0)	10	No	Yes	No	n = 11 Amateur soccer players	6x 6 s sprint 20 s between efforts; 2 testing sessions; 7 days between sessions

Reference	Device (model)	Sampling rate (Hz)	Intra-day reliability	Inter-day reliability	Validity	Sample	Study description
(Rumpf, 2012)	NMT (Woodway Force 3.0)	200	No	Yes	No	n = 25 Athletic males (8-13 yo)	3x 5 s sprint, stationary start 4 min between efforts; 3 testing sessions; 3-7 days between sessions
(Cross, Brughelli, & Cronin, 2014)	NMT (Woodway Force 3.0)	200	Yes	No	No	n = 7 Male university-level athletes	2x 6 s maximal sprints < 4 min rest between trials; standing "blocked" start
(Nédélec et al., 2013)	NMT (Woodway Force 3.0)	100	No	Yes	No	n = 13 Professional soccer players	3x 6 s sprints 3 min between efforts; standing start
(Takai et al., 2013)	NMT (Custom built model D-08011d)	100	No	No	Yes	n= Pilot sample from 94 total Boys (avg13.7 yo)	Preliminary study compared NMT and over-ground sprinting speed
(Zois, Bishop, Fairweather, Ball, & Aughey, 2013)	NMT (Woodway Force)	25	Yes	No	No	n = 8 Male, amateur soccer players	3x 4 s maximal sprints 14 s passive recovery between efforts
(Jaskolski, Veenstra, Goossens, Jaskolska, & Skinner, 1996)	TT (Gymrol Sprint 1800)	100	No	Yes	No	n = 35 Male students	6x 5 s maximal sprints (against resistances of 5,8,10,13,15,20% of the treadmill's maximal resistance of 1352 N) 5 min between efforts; 2 testing sessions
(Chelly & Denis, 2001)	TT (Sprint Club)	NR	No	No	Yes	n = 11 Male, handball players	1x 8 s sprint from standing start (TT), compared to 1x 40 m over-ground sprint (radar)
(Lim & Chia, 2007)	TT (Sprint Club 2000)	100	Yes	Yes	Yes	n = 18 (9 M, 9 F) All untrained	2x 10 s sprints from a walking start. Repeated 2 weeks later
(Chia & Lim, 2008)	TT (Sprint Club 2000)	100	No	No	Yes	n = 23 (12M 11F) Sedentary adults	1x 10 s sprint from a walking start (TT), compared to 1x 10 s cycle sprint (WAnT)
(Morin et al., 2010)	TT (Custom ADAL3D-WR)	1000	Yes	No	No	n = 8 Male PE students (Pilot study)	1x 6 s maximal sprint Repeated within two weeks; standing “blocked” start
(Morin et al., 2011)	TT (Custom ADAL3D-WR)	1000	No	No	Yes	n = 12 Male PE students	1x 8 s sprint from a standing start (TT), compared to 1x 100 m over-ground sprint (radar)
(Morin & Seve, 2011)	TT (Custom ADAL3D-WR)	1000	No	No	Yes	n = 11 Male PE students	1x 100 m on TT Compared to 1x 100 m on track (radar); standing “blocked” start

Note. NMT = non-motorised treadmill; NR = not reported; TT = torque treadmill; PE = physical education; F_h = horizontal ground reaction force; yo = years old; M = male; F = female; WAnT = Wingate anaerobic test on bicycle ergometer; Avg = average

[a] Reliability and validity testing also completed from the analysis of longer (30 s) sprints, as well as submaximal effort sprints

Radar and laser technology enable instantaneous measures of horizontal distance, speed, acceleration and F_h during linear over-ground sprinting. The raw speed data typically contains some irregularities (i.e. intermittently unexpected high and low results), which Chelly and Denis (2001) suggested are likely caused by segmental movements and acceleration-deceleration of the body while running. Authors utilising laser technology have smoothed the raw data by filtering (Delecluse et al., 2005), applying a moving average over 0.30 s (Debaere et al., 2013) or applying a fourth- or fifth-order polynomial function (Bezodis et al., 2012). Di Prampero et al. (2005) measured speed with a radar gun and fitted the speed-time curve to an exponential function, which described the actual running speed from the radar device very accurately ($r^2 = 0.99$):

$$s(t) = s_{max} * (1 - e^{-t/\tau})$$

Where s is the modeled running speed, s_{max} is the maximal velocity achieved during the sprint, t is the time and τ is the time constant. The leveling off section of the speed-time curve signifies s_{max} and time to reach this maximal velocity provides a measure of acceleration.

In more recent studies of longer (100 m) sprints the speed-time curve was fitted to a biexponential curve (Chelly & Denis, 2001; Morin et al., 2006; Morin & Seve, 2011):

$$s(t) = s_{max} * [e^{((-t+tsmax)/\tau 2)} - e^{(-t/\tau 1)}]$$

Where t_{smax} is the time to reach maximal velocity, and $\tau 1$ and $\tau 2$ are the time constants for acceleration and deceleration respectively (Figure 4). Speed data modeled in this way also proved to have a very strong correlation with actual speed results ($r^2 = 0.99$) (Morin & Seve, 2011).

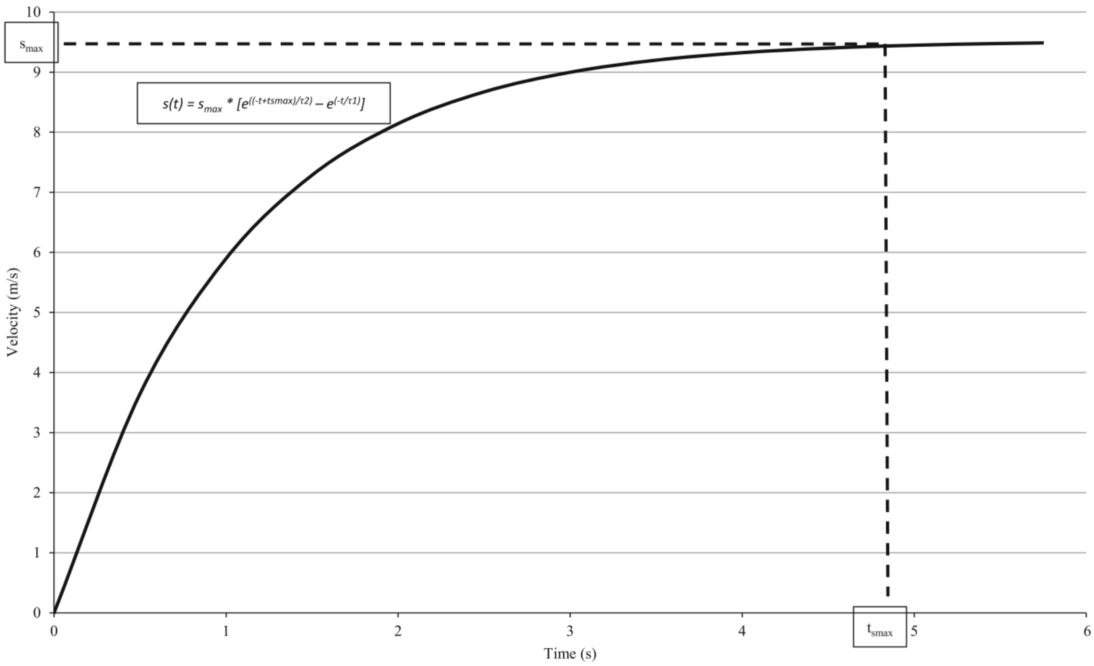

Figure 4. Example of a modeled speed-time curve from radar data. Where s_{max} is the maximum speed achieved, $\tau 1$ and $\tau 2$ are the time constants for acceleration and deceleration respectively, and t_{smax} is the time taken to reach maximum speed.

Instantaneous forward acceleration can be calculated from the simple first derivative of either equation for s(t) above, and distance can be calculated from the time integral of the equation. In addition to s_{max} and t_{smax}, variables of interest for sprinting performance can include: time to reach a certain distance; mean speed over a certain distance; percentage drop in velocity at the end of an effort; and maximal or average acceleration. The radar and laser devices have been used to test subjects over 10-100 m (Table 1), however the instantaneous nature of the data means that any straight-line distance can be measured. In order to provide a more meaningful result for team sport athletes that are concerned with acceleration ability, the distance covered in 4 s (d_{4sec}) has been utilised (Morin et al., 2011), although considering the demands of most team sports, sprint performance over even shorter distances and time periods would also be of interest in the future.

An additional benefit of the radar and laser systems is that given the instantaneous forward acceleration (a) of an individual with a known body mass (m), F_h can be easily calculated from Newton's second law of motion (Morin & Seve, 2011):

$$F_h = m * a$$

Morin and Seve (2011) also added an estimation of the horizontal force produced against air friction (F_{air}) to give a net horizontal force estimated from over-ground sprinting ($F_{h\text{-}field}$) using the radar system:

$$F_{h\text{-}field} = F_h + F_{air}$$

Horizontal force can then be plotted against horizontal velocity (Figure 5) (Samozino et al., 2015), to provide a force-velocity profile that is perhaps more relevant for team sport athletes than a force-velocity profile from vertically-oriented exercises (e.g. power clean or squat jump) performed on a force platform. The x- and y-axis intercept values (F0 and V0) represent the theoretical maximal horizontal force at zero velocity and the theoretical maximal horizontal velocity at zero load respectively. Samozino, Rejc, Di Prampero, Belli, and Morin (2012) recommended using the slope of the linear F-v profile (S_{Fv}) determined from jump testing in order to enable a comparison between individuals independent of their power capabilities.

$$S_{Fv} = - F0 / V0$$

The S_{Fv} results can theoretically be used to identify relatively force-dominant (*F-dom*) (i.e. a steeper negative slope) and relatively velocity-dominant (*v-dom*) (i.e. a flatter negative slope) athletes and to guide subsequent training interventions (Samozino, Morin, Hintzy, & Belli, 2010; Samozino et al., 2012). Longitudinal applications of this theory are required to determine the efficacy of the technique, particularly given the multifactorial nature of sprinting.

Power (*P*) can be calculated from the product of F_h and s:

$$P = F_h * s$$

The peak of the parabolic power-velocity (*P-v*) relationship indicates the point of peak power output (Pmax) (Figure 5). Pmax can also be calculated using the values for F0 and V0 (Samozino et al., 2015):

$$Pmax = (F0 * V0) / 4$$

Deceleration is another component of speed that is frequently observed in team sport competition (Lakomy & Haydon, 2004). Radar and laser technology provide a means to profile straight-line deceleration ability in more detail than was previously possible. Despite this, there have been no reports to date regarding the reliability of radar-derived deceleration results.

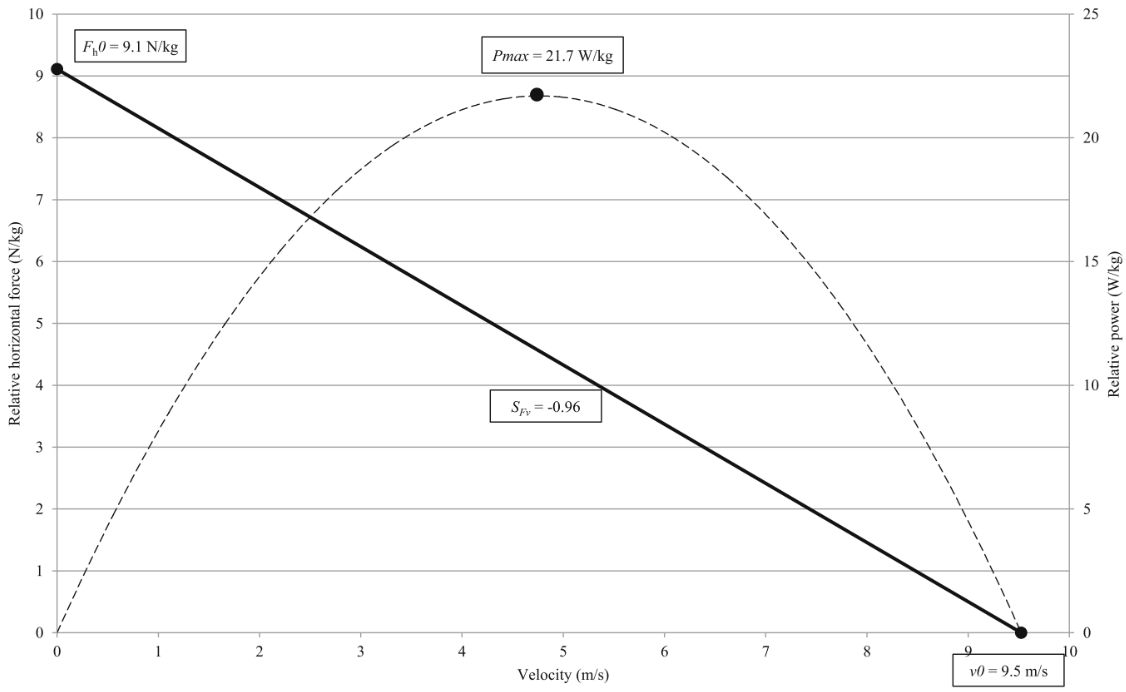

Figure 5. Example of force-velocity and power-velocity profiles from measurements made with a radar device for an individual with the following physical characteristics: theoretical maximum force (F_h0) = 9.1 N/kg; theoretical maximum velocity (V0) = 9.5 m/s; slope of the force-velocity profile (S_{Fv}) = -0.96; and, maximum power output (P_{max}) = 21.7 W/kg.

Reliability

Ferro et al. (Ferro et al., 2012) are the only authors to date that have reported both absolute and relative reliability for both intra-day and inter-day repeated measurements using radar or laser technology (Table 1 and Table 2). Intra-day absolute and relative reliability of speed and acceleration was acceptable across all studies (CV ≤ 9.5%; systematic error (bias) ≤ 4.1%; ICC/r ≥ 0.84) (Debaere et al., 2013; Delecluse et al., 2005; di Prampero et al., 2005; Ferro et al., 2012); however the number of repeated trials and/or the time between trials was not always reported (Debaere et al., 2013; Delecluse et al., 2005; di Prampero et al., 2005). In the only between day comparison to date, relative reliability was acceptable and ICC values only dropped below 0.84 for mean and maximum velocity for the initial 10 m (ICC = 0.76 and 0.73 respectively) and maximum velocity between 20 m and 30 m (ICC = 0.72) (Ferro et al., 2012). CV values were not reported for inter-day absolute reliability; however all systematic error (bias) values were no higher than 6% (Ferro et al., 2012). No assessment of the reliability of measures of time to complete a range of distances between 2 m and 30 m has been reported in the literature.

The intra-day absolute and relative reliability of the measures of F0, V0, Pmax and S_{Fv} derived from laser was acceptable for all outcomes (CV = 1.6-8.9%; ICC = 0.87-0.97), except F0 which had acceptable absolute (CV = 7.8%) but not relative reliability (ICC = 0.64) (Buchheit et al., 2014). Acceptable intra-day absolute reliability was also reported for F0, V0, Pmax, S_{Fv} and D_{RF} derived from a radar device (CV = 1.1-4.0%; standard error of measurement = 1.4-5.0%) within a population of high-level sprinters (Samozino et al., 2015). An assessment of the inter-day reliability of all kinetic measures from radar and laser technology has not been reported in the literature.

Validity

Researchers validating the use of radar and laser technology have consistently demonstrated very strong agreement between sprint results using radar/laser and photoelectric cells (Berthoin et al., 2001; di Prampero et al., 2005; Ferro et al., 2012; Morin et al., 2006) (see concurrent validity results in Table 2). A strong linear relationship between radar and photoelectric cell split-time results (t_{radar} and $t_{photocells}$ respectively) was reported when photoelectric cells were positioned every 10 m during a 100 m maximal sprint ($t_{radar} = 1.01 * t_{photocells} – 0.06$; $r^2=0.99$, $p < 0.01$) (di Prampero et al., 2005; Morin et al., 2006). Additionally, Chelly and Denis (2001) measured moving subjects and rolling balls with given speeds between 1 and 22 m/s over a 3 m distance and a strong linear correlation was observed between the radar speed (s_{radar}) and simultaneously-collected photoelectric cell speed ($s_{photocells}$) measurements ($s_{radar} = 0.99 * s_{photocells} + 0.22$; $r^2=0.99$).

Compared to the criterion measurement of velocity from high-speed video, Gander et al. (1994) reported that radar measurements were approximately 3.3% lower over a range of distances (10-30 m). The magnitude of the bias and random error between laser and video results was reported to be influenced by how far away the sprinter was from the laser (Bezodis et al., 2012; Ferro et al., 2012), but did not appear to be influenced by the velocity of the sprinter (Bezodis et al., 2012). Bezodis et al. (2012) concluded that the unacceptable level of error during the initial 5 m of the 50 m sprint was due largely to the subjects becoming increasingly upright during this initial acceleration. The distance between the lumbar point (where the laser was focused) and the COM of the subject was approximately 0.40 m at the start of the sprint, but reduced to approximately 0.15 m after just 1 s.

Samozino et al. (2015) recently reported the first comparison between F_h measured with radar and a series of embedded force platforms during over-ground sprinting. Absolute bias of 3-7% between radar and force platform values was reported for F0, V0, Pmax, S_{Fv} and D_{RF}. In contrast the authors reported absolute bias of 2-5% between timing lights and the force platform data for F0, V0, Pmax. Absolute bias for S_{Fv} and D_{RF} from timing lights was 6-8% (Samozino et al., 2015). In addition, two studies have compared the agreement between radar and torque treadmill measurements of F_h over a 100 m sprint (Morin et al., 2011; Morin & Seve, 2011). The force values measured with the radar gun were lower than that of the torque treadmill by on average 79.7 ± 6.9 N (~12% of body weight). The average difference during the acceleration up to s_{max} was 69.9 ± 8.5 N (~10% of body weight) and during the section after s_{max} the average difference was reported to be significantly higher at 86.7 ± 8.1 N ($p < 0.001$) (~13% of body weight). The differences in F_h between the track and treadmill conditions were significantly correlated with treadmill values for mean F_v relative to body mass ($r = 0.69$; $p = 0.02$), but were not correlated with body mass or F_h. The added force that is required to overcome the inherent friction in the treadmill system means that even at s_{max} the treadmill F_h values do not reach zero as would be expected during over-ground sprinting where F_h values approach zero (but remain positive due to the need to overcome air resistance). The track measurements of F_h from the radar gun do however reach approximately zero at s_{max} and negative values during the small deceleration towards the end of the 100 m sprint. (Morin et al., 2011; Morin & Seve, 2011). The radar-derived values for F_h also tend to be more consistent than the treadmill-derived values.

Table 2. Reliability and validity results from radar and laser technology.

Reference	Reliability / validity	Variables	Mean1 [a]	Mean2	Absolute reliability: CV (%) (CI)	Absolute reliability: LoA	Relative reliability: ICC (CI)	Relative reliability: r
(Gander et al., 1994)	Concurrent validity (radar vs video)	Velocity (at 10-30 m) (m/s)	8.91 [b]	9.21 [c]				
(Gander et al., 1994)	Concurrent validity (radar vs photocells)	Mean time to reach 20 m (s)	3.33 [b]	3.38 [d]				0.976
(Chelly & Denis, 2001)	Concurrent validity (radar vs photocells)	Velocity (m/s)						0.99
(di Prampero et al., 2005)	Intra-day reliability (radar)	Peak velocity (m/s) Peak acceleration (m/s/s)	9.46 ± 0.19 6.42 ± 0.61		2.0 9.5			
	Concurrent validity (radar vs photocells)	Time on each 10 m of 100 m (s)						0.99
(Morin et al., 2006)	Concurrent validity (radar vs photocells)	Time on each 10 m of 100 m (s)						0.99
(Morin & Seve, 2011)	Concurrent validity (radar vs modelled)	Speed - actual vs modelled (m/s)						0.997
(Berthoin et al., 2001)	Concurrent validity (laser vs photocells)	Time to 20 and 50 m (s)						0.99
(Delecluse et al., 2005)	Intra-day reliability (laser)	Velocity at 5 m intervals (5-30 m)						0.95-0.98
(Bezodis et al., 2012)	Concurrent validity (laser vs video)	Velocity @ 1 m (m/s) Velocity @ 5 m (m/s) Velocity @ 10 m (m/s) Velocity @ 30 m (m/s) Velocity @ 50 m (m/s)	4.00 ± 0.15 [e] 6.01 ± 0.23 [e] 7.30 ± 0.29 [e] 8.52 ± 0.62 [e] 10.38 ± 0.31 [e]			0.41 ± 0.18 0.13 ± 0.21 0.16 ± 0.11 0.06 ± 0.13 0.08 ± 0.15		

					Absolute reliability		Relative reliability	
Reference	Reliability / validity	Variables	Mean1 [a]	Mean2	CV (%) (CI)	LoA	ICC (CI)	r
(Ferro et al., 2012)	Intra-day reliability (laser)	Mean velocity 0-10 m (m/s)	5.51 ± 0.16	5.53 ± 0.17		-0.09 ± 0.14	0.94 (0.86-0.98)	
		Mean velocity 10-20 m (m/s)	8.04 ± 0.21	8.04 ± 0.19		-0.14 ± 0.15	0.94 (0.86-0.98)	
		Mean velocity 20-30 m (m/s)	8.60 ± 0.23	8.58 ± 0.23		-0.16 ± 0.12	0.96 (0.90-0.98)	
		Max velocity 0-10 m (m/s)	7.57 ± 0.24	7.55 ± 0.25		-0.31 ± 0.27	0.84 (0.64-0.93)	
		Max velocity 10-20 m (m/s)	8.61 ± 0.23	8.58 ± 0.21		-0.24 ± 0.18	0.89 (0.75-0.95)	
		Max velocity 20-30 m (m/s)	8.92 ± 0.27	8.90 ± 0.29		-0.30 ± 0.29	0.87 (0.71-0.95)	
	Inter-day reliability (laser)	Mean velocity 0-10 m (m/s)	5.53 ± 0.16	5.56 ± 0.23		-0.25 ± 0.32	0.76 (0.46-0.91)	
		Mean velocity 10-20 m (m/s)	8.04 ± 0.21	7.98 ± 0.21		-0.28 ± 0.16	0.88 (0.70-0.95)	
		Mean velocity 20-30 m (m/s)	8.59 ± 0.23	8.51 ± 0.30		-0.40 ± 0.24	0.84 (0.61-0.94)	
		Max velocity 0-10 m (m/s)	7.55 ± 0.24	7.47 ± 0.36		-0.46 ± 0.30	0.73 (0.39-0.89)	
		Max velocity 10-20 m (m/s)	8.58 ± 0.21	8.47 ± 0.26		-0.38 ± 0.15	0.85 (0.64-0.94)	
		Max velocity 20-30 m (m/s)	8.88 ± 0.22	8.85 ± 0.32		-0.45 ± 0.40	0.72 (0.38-0.89)	
	Concurrent validity (laser vs video)	Mean velocity (m/s)	8.56 ± 0.30 [f]	8.45 ± 0.30 [e]		-0.27 ± 0.06		0.96 (0.90-0.99)
		Max velocity (m/s)	8.81 ± 0.34 [f]	8.95 ± 0.36 [e]		-0.21 ± 0.49		0.87 (0.68-0.95)
	Concurrent validity (laser vs photocells)	Mean velocity 0-10 m (m/s)	5.54 ± 0.22 [f]	5.25 ± 0.21 [d]		-0.46 ± 0.13		0.93 (0.87-0.96)
		Mean velocity 10-20 m (m/s)	7.96 ± 0.27 [f]	7.92 ± 0.28 [d]		-0.16 ± 0.09		0.97 (0.95-0.99)
		Mean velocity 20-30 m (m/s)	8.49 ± 0.34 [f]	8.50 ± 0.35 [d]		-0.12 ± 0.14		0.99 (0.97-0.99)
(Debaere et al., 2013)	Intra-day reliability (laser)	Acceleration 0-10 m (m/s/s)	3.74 ± 0.24 [g]	3.51 ± 0.24 [h]			0.97	
		Acceleration 10-30 m (m/s/s)	0.74 ± 0.06 [g]	0.55 ± 0.04 [h]			0.87	
		Max velocity (m/s)	10.01 ± 0.16 [g]	8.88 ± 0.11 [h]			0.98	
(Buchheit et al., 2014)	Intra-day reliability (laser)	V0 (m/s)			1.6		0.97	
		Relative *F0* (N/kg)			7.8		0.64	
		Relative max power output (N/kg)			7.1		0.87	
		Force-velocity profile (slope)			8.9		0.88	
(Samozino et al., 2015)	Intra-day reliability (radar)	*V0* (m/s)		-0.17 ± 0.78 [i]	1.1 ± 0.9			
		F0 (N)		-1.53 ± 32.2 [i]	2.9 ± 2.0			
		Max power output (W)		-0.17 ± 0.66 [i]	1.9 ± 1.4			
		S_{Fv} (N/s/m)		-0.20 ± 4.18 [i]	4.0 ± 2.7			
		D_{RF} (%/s/m)		-0.11 ± 0.45 [i]	4.0 ± 2.8			

Note. CV = coefficient of variation; CI = confidence interval: LoA = limits of agreement; ICC = intraclass correlation coefficient; r = correlation coefficient; Max = maximum; *v0* = theoretical maximum velocity; F0 = theoretical maximum horizontal force; Pmax = maximum power output; S_{Fv} = slope of the force-velocity relationship; D_{RF} = rate of linear decrease in the ratio of the net horizontal and resultant ground reaction forces

[a] When mean2 data are absent in the table, mean1 data represent the "grand mean" of the study; [b] Radar data; [c] Video data; [d] Photocell data; [e] High-speed video data; [f] Laser data; [g] Male results; [h] Female results; [i] When mean1 data are absent in the table, mean2 data represent the change in the mean

Non-Motorised Treadmill (NMT) and Torque Treadmill Technology

Utility in Speed Profiling

The earliest study of maximal acceleration sprinting on a NMT established the sequential relationship between maximum values for F_h, power and speed; however F_v could not be measured (Lakomy, 1987). A limitation of this study and a number of subsequent studies is that kinematic and kinetic values from NMT/torque treadmill analysis have often been averaged over arbitrary time windows such as 1 s (Chia & Lim, 2008; Highton et al., 2012; Hughes et al., 2006; Jaskolski et al., 1996; Lakomy, 1987; Oliver et al., 2006; Sirotic & Coutts, 2008; Tong et al., 2001) or an entire sprint (Chia & Lim, 2008; Hughes et al., 2006; Jaskolski et al., 1996; Lakomy, 1987; Lim & Chia, 2007). Modern, commercially available NMT/torque treadmill ergometers (e.g. Woodway Force, Eugene, OR, USA) can now also measure F_v during sprinting, and provide detailed data from the period of ground contact during each sprinting step (e.g. Cross et al., 2014) that could otherwise not be obtained without extended running tracks instrumented with expensive force platforms.

Stepwise values of F_h from the step at maximal F_h to the step at s_{max} can be plotted against running speed to form a linear force-velocity relationship from one maximal sprint (Morin et al., 2010). For NMT/torque treadmill models that assess F_h indirectly, the stepwise peak F_h values may not align perfectly with the period of each foot contact, so F_h may instead be calculated from the product of m and a. Analogous to the use of radar technology (Figure 5), NMT/torque treadmill sprint analysis provides force-velocity profile intercepts (F0 and V0) and Pmax values that can be used to help direct subsequent speed training programs.

Added benefits of NMT/torque treadmill technology include the ability to assess bilateral limb balance for a number of kinematic and kinetic variables (Brughelli et al., 2010) and also the measurement of F_v, which is not possible with radar and laser technology. The ability to measure F_v and total GRF (F_{tot}) enables the calculation of the ratio of forces F_h relative to F_{tot} (RF). Morin et al. (2011) proposed an index of force application technique (D_{RF}) to be the slope of the RF-speed relationship. During acceleration from a standing start, RF decreases linearly with the increase in speed. A high D_{RF} will indicate that more RF is maintained as speed increases, and this index is highly correlated (r = 0.74-0.78) with sprint acceleration and 100 m performance (Morin et al., 2011).

Reliability

The combined NMT/torque treadmill reliability results from short maximal acceleration sprints of ≤ 10 s are summarised for kinematic and kinetic variables in Table 3 and Table 4, respectively. The NMT results tend to provide support for previous conclusions that kinematic variables are more reliable than kinetic variables (Hughes et al., 2006; Sirotic & Coutts, 2008), mean values tend to be more reliable than peak values (Hopker et al., 2009; Hughes et al., 2006; Tong et al., 2001), and longer sprints tend to be more reliable than shorter sprints (Highton et al., 2012; Sirotic & Coutts, 2008). With only one exception (Rumpf, 2012), all authors that analysed data from specific sprint steps rather than averaging over arbitrary time windows or an entire sprint, reported acceptable levels of reliability (Cross et al., 2014; Morin et al., 2010; Yanagiya et al., 2003; Yanagiya et al., 2004).

After sufficient familiarisation with sprinting on a NMT, the absolute reliability of the kinematic variables was typically very good with all CV values below 10%, except time to peak speed during a 30 m sprint (Highton et al., 2012), the decrement in maximal speed during repeated 6 s sprints (Hughes et al., 2006) and the initial acceleration over the first 0.5 s of a sprint (Zois et al., 2013). The RLoA results from the study of Highton et al. (2012) also indicated high random error values for speed at 1 s, but acceptable levels of error for speed at 2 s and 3 s. Relative reliability has been less thoroughly investigated, but after sufficient familiarisation all reported ICC values were ≥ 0.83 except the average step rate results (ICC = 0.46) in a population of children (Rumpf, 2012).

Kinetic variables measured on NMT typically have reduced reliability compared to kinematic variables; however, CVs for all measures of F_h and F_v were still < 10% (except when testing was intentionally completed prior to sufficient treadmill familiarisation (Hopker et al., 2009)). Some power results from short (20 m, 3 s and 4 s) sprints had CVs in excess of 10% (Hopker et al., 2009; Serpiello et al., 2011; Sirotic & Coutts, 2008). Relative reliability of kinetic variables was unacceptably low (ICC < 0.70) for some measures of F_h and F_v (Hopker et al., 2009; Rumpf,

2012) and power output from short (20 m and 3 s) sprints (Hopker et al., 2009; Sirotic & Coutts, 2008). Several authors did however report acceptable relative reliability (ICC and r > 0.80) for F_h, F_v and power output (Cross et al., 2014; Hopker et al., 2009; Nédélec et al., 2012; Nédélec et al., 2013; Rumpf, 2012; Sirotic & Coutts, 2008; Sweeney et al., 2010). Insufficient familiarisation (Hopker et al., 2009), a rolling sprint start protocol (Hopker et al., 2009), analysis of arbitrary time windows (Sirotic & Coutts, 2008) and a youth population (Rumpf, 2012) appear to be associated with unacceptable reliability of kinetic results from a NMT particularly for between day comparisons.

The more limited volume of results addressing torque treadmill reliability generally indicate acceptable levels of absolute (CV ≤ 5.8%) and relative (ICC > 0.80) reliability for kinetic measures, and acceptable levels of relative reliability (ICC ≥ 0.81) for kinematic measures (Jaskolski et al., 1996; Lim & Chia, 2007). Absolute reliability of kinematic measures on a torque treadmill has not been reported in the literature. Even when power output was assessed against a range of treadmill resistances, acceptable inter-day relative reliability was reported for the measurement of power on a torque treadmill (ICC = 0.76-0.94) (Jaskolski et al., 1996).

Validity

The concurrent validity of the NMT and torque treadmill has been assessed through comparisons with over-ground sprinting performance measured with high-speed video (30 s sprint) (Lakomy, 1987), photoelectric cells (Highton et al., 2012; Hopker et al., 2009), radar (Chelly & Denis, 2001; Morin et al., 2011; Morin & Seve, 2011) and one study in which the over-ground measurement technique was not reported (Takai et al., 2013) (Table 5). Additionally, power output measured on a torque treadmill and also on a Wingate anaerobic cycle test was compared and found to be very strongly correlated (≥ 0.83) (Chia & Lim, 2008).

Table 3. Reliability of kinematic results from NMT and torque treadmill technology (all reliability testing is for NMT unless stated).

					Absolute reliability				Relative reliability
Reference	Reliability	Variables	Mean1 [a]	Mean2	CV (%) (CI)	SEM (CI)	LoA	Ratio LoA	ICC (CI)
(Jaskolski et al., 1996)	Inter-day reliability (TT)	Velocity (m/s)							0.81-0.91
(Tong et al., 2001)	Intra-day reliability	Max avg speed (m/s)	7.07 ± 0.30	7.08 ± 0.24	1.9		0.01 ± 0.27	1.00 ×/÷ 1.03	
		Max instantaneous speed (m/s)	7.53 ± 0.31	7.57 ± 0.29	1.7		0.04 ± 0.26	1.05 ×/÷ 1.03	
	Inter-day reliability	Max avg speed (m/s)	7.07 ± 0.25	7.05 ± 0.27	1.3		0.02 ± 0.18	1.03 ×/÷ 1.03	
		Max instantaneous speed (m/s)	7.68 ± 0.30	7.64 ± 0.28	1.3		0.04 ± 0.35	1.00 ×/÷ 1.03	
(Hughes et al., 2006)	Inter-day reliability (trial 1-2)	Mean 1 s MxSP (m/s)	7.21		1.8 (1.1-3.0)	0.09 (0.06- -0.17)		1.00 ×/÷ 1.04	
		Percent decrement MxSP (%)	2.38		22.9 (13.4-37.9)	0.38 (0.26-0.70)		1.22 ×/÷ 1.55	
	Inter-day reliability (trial 2-3)	Mean 1 s MxSP (m/s)	7.19		1.8 (1.0-3.1)	0.09 (0.06- -0.17)		1.01 ×/÷ 1.04	
		Percent decrement MxSP (%)	2.26		50.0 (28.3-86.0)	0.80 (0.54-1.53)		0.87 ×/÷ 2.45	
	Combined reliability (3 sessions of 6 sprints)	Mean 1 s MxSP (m/s)	7.17 ± 0.33		2.8 (1.9-3.9)				
		Percent decrement MxSP (%)	2.37 ± 1.09		31.5 (21.7-44.5)				
(Oliver et al., 2006)	Inter-day reliability (all trials)	Peak velocity (m/s)	6.10		2.88 (2.34-3.74)				
		Mean velocity (m/s)	4.93		2.59 (2.11-3.36)				
(Sirotic & Coutts, 2008)	Inter-day reliability (trial 1-2)	6 s Distance (m)	37.23		2.5 (1.7-4.4)			1.02 ×/÷ 1.07	0.85 (0.51-0.96)
		6 s Mean max 1 s sprint speed (m/s)	7.29		1.3 (0.9-2.4)			1.01 ×/÷ 1.04	0.94 (0.79-0.99)
		3 s Distance (m)	17.87		6.2 (4.4-11.4)			1.05 ×/÷ 1.18	0.58 (-0.04-0.87)
		3 s Mean max 1 s sprint speed (m/s)	7.10		1.8 (1.3-3.3)			1.01 ×/÷ 1.05	0.90 (0.65-0.97)
	Inter-day reliability (trial 2-3)	6 s Distance (m)	37.59		1.3 (0.9-2.4)			1.00 ×/÷ 1.04	0.93 (0.75-0.98)
		6 s Mean max 1 s sprint speed (m/s)	7.33		1.3 (0.9-2.4)			1.01 ×/÷ 1.04	0.94 (0.79-0.99)
		3 s Distance (m)	18.27		1.8 (1.3-3.3)			1.00 ×/÷ 1.05	0.90 (0.64-0.97)
		3 s Mean max 1 s sprint speed (m/s)	7.19		1.7 (1.2-3.0)			1.01 ×/÷ 1.05	0.92 (0.70-0.98)
(Hopker et al., 2009)	Inter-day reliability (all trials)	Time to 20 m (s)			5.5 (4.7-6.6)				
(Serpiello et al., 2011)	Intra-day reliability	Peak velocity (m/s)			3.5				
		Mean velocity (m/s)			2.6				

Reference	Reliability	Variables	Mean1 [a]	Mean2	Absolute reliability				Relative reliability
					CV (%) (CI)	SEM (CI)	LoA	Ratio LoA	ICC (CI)
(Highton et al., 2012)	Inter-day reliability	Time to 10 m (s)	2.39 ± 0.17	2.30 ± 0.22	4.2		0.09 ± 0.34	1.04 ×/÷ 1.16	
		Time to 20 m (s)	4.23 ± 0.26	4.13 ± 0.25	2.8		0.10 ± 0.37	1.02 ×/÷ 1.09	
		Time to 30 m (s)	6.10 ± 0.36	6.00 ± 0.30	2.2		0.11 ± 0.42	1.02 ×/÷ 1.07	
		Time 10-20 m (s)	1.80 ± 0.11	1.82 ± 0.11	2.3		0.02 ± 0.14	1.01 ×/÷ 1.08	
		Time 20-30 m (s)	1.83 ± 0.11	1.83 ± 0.14	2.9		-0.01 ± 0.19	0.99 ×/÷ 1.12	
		Peak instantaneous speed (m/s)	5.62 ± 0.28	5.60 ± 0.26	1.8		-0.02 ± 0.35	1.00 ×/÷ 1.06	
		Peak avg speed (m/s)	5.56 ± 0.28	5.54 ± 0.26	1.8		-0.02 ± 0.33	1.00 ×/÷ 1.06	
		Mean speed (m/s)	4.94 ± 0.27	5.02 ± 0.25	2.1		-0.08 ± 0.33	0.99 ×/÷ 1.07	
		Time to peak speed (s)	3.41 ± 0.73	3.09 ± 0.65	10.8		0.32 ± 1.16	1.10 ×/÷ 1.47	
		Step length (m/step)	1.16 ± 0.09	1.16 ± 0.99	2.3		-0.01 ± 0.09	0.99 ×/÷ 1.09	
		Step frequency(steps/s)	4.43 ± 0.33	4.48 ± 0.33	1.6		0.06 ± 0.25	1.01 ×/÷ 1.06	
		Speed at 1 s (m/s)	4.06 ± 0.60	4.03 ± 0.60			-0.03 ± 0.93	0.99 ×/÷ 1.28	
		Speed at 2 s (m/s)	5.14 ± 0.40	5.20 ± 0.41			0.05 ± 0.41	1.01 ×/÷ 1.08	
		Speed at 3 s (m/s)	5.46 ± 0.29	5.42 ± 0.40			-0.03 ± 0.29	0.99 ×/÷ 1.06	
	Intra-day reliability (Day 1)	Time to 10 m (s)	2.48 ± 0.24	2.50 ± 0.24	2.8		-0.02 ± 0.33	0.99 ×/÷ 1.14	
		Time to 20 m (s)	4.28 ± 0.26	4.34 ± 0.34	1.7		-0.06 ± 0.31	0.99 ×/÷ 1.07	
		Time to 30 m (s)	6.16 ± 0.36	6.23 ± 0.42	1.8		-0.07 ± 0.39	0.99 ×/÷ 1.06	
		Time 10-20 m (s)	1.80 ± 0.11	1.85 ± 0.14	1.9		-0.04 ± 0.16	1.02 ×/÷ 1.08	
		Time 20-30 m (s)	1.88 ± 0.11	1.89 ± 0.13	3.0		-0.01 ± 0.22	0.99 ×/÷ 1.13	
		Peak instantaneous speed (m/s)	5.58 ± 0.26	5.55 ± 0.33	1.2		0.03 ± 0.27	1.01 ×/÷ 1.07	
		Peak avg speed (m/s)	5.52 ± 0.26	5.50 ± 0.33	1.1		-0.02 ± 0.26	0.95 ×/÷ 1.05	
		Mean speed (m/s)	4.89 ± 0.26	4.81 ± 0.37	2.4		0.08 ± 0.52	1.02 ×/÷ 1.12	
		Time to peak speed (s)	3.78 ± 0.75	3.76 ± 0.98	8.1		0.02 ± 1.11	1.02 ×/÷ 1.33	
		Step length (m/step)	1.14 ± 0.08	1.13 ± 0.07	1.7		-0.01 ± 0.08	0.99 ×/÷ 1.07	
		Step frequency(steps/s)	4.37 ± 0.37	4.43 ± 0.33	1.4		0.04 ± 0.23	1.01 ×/÷ 1.05	
		Speed at 1 s (m/s)	3.93 ± 0.86	4.21 ± 0.44			0.28 ± 1.30	1.09 ×/÷ 1.49	
		Speed at 2 s (m/s)	5.16 ± 0.46	5.25 ± 0.28			0.09 ± 0.56	1.02 ×/÷ 1.12	
		Speed at 3 s (m/s)	5.47 ± 0.28	5.48 ± 0.28			0.01 ± 0.23	1.00 ×/÷ 1.04	

					Absolute reliability				Relative reliability
Reference	Reliability	Variables	Mean1 [a]	Mean2	CV (%) (CI)	SEM (CI)	LoA	Ratio LoA	ICC (CI)
	Intra-day reliability (Day 2)	Time to 10 m (s)	2.51 ± 0.34	2.41 ± 0.16	5.1		0.10 ± 0.50	1.03 ×/÷ 1.20	
		Time to 20 m (s)	4.34 ± 0.39	4.24 ± 0.19	3.1		0.10 ± 0.52	1.02 ×/÷ 1.12	
		Time to 30 m (s)	6.20 ± 0.44	6.11 ± 0.26	2.1		0.09 ± 0.47	1.01 ×/÷ 1.07	
		Time 10-20 m (s)	1.83 ± 0.09	1.83 ± 0.09	0.7		0.00 ± 0.05	1.00 ×/÷ 1.03	
		Time 20-30 m (s)	1.85 ± 0.16	1.87 ± 0.11	1.9		-0.02 ± 0.16	0.99 ×/÷ 1.09	
		Peak instantaneous speed (m/s)	5.53 ± 0.27	5.55 ± 0.26	1.2		-0.02 ± 0.24	1.00 ×/÷ 1.04	
		Peak avg speed (m/s)	5.48 ± 0.27	5.50 ± 0.26	1.1		0.02 ± 0.21	1.00 ×/÷ 1.04	
		Mean speed (m/s)	4.85 ± 0.35	4.92 ± 0.21	2.3		-0.08 ± 0.40	0.98 ×/÷ 1.08	
		Time to peak speed (s)	3.65 ± 0.98	3.52 ± 0.88	10.8		0.13 ± 1.58	1.03 ×/÷ 1.49	
		Step length (m/step)	1.11 ± 0.08	1.14 ± 0.10	2.6		0.04 ± 0.10	1.03 ×/÷ 1.09	
		Step frequency(steps/s)	4.41 ± 0.37	4.37 ± 0.38	1.5		-0.05 ± 0.25	0.99 ×/÷ 1.06	
		Speed at 1 s (m/s)	4.24 ± 0.39	4.45 ± 0.53			0.21 ± 0.85	1.05 ×/÷ 1.22	
		Speed at 2 s (m/s)	5.28 ± 0.29	5.23 ± 0.31			0.05 ± 0.34	1.01 ×/÷ 1.06	
		Speed at 3 s (m/s)	5.49 ± 0.30	5.52 ± 0.27			0.03 ± 0.29	1.01 ×/÷ 1.05	
(Rumpf, 2012)	Inter-day reliability (all trials)	Avg velocity (m/s)	2.55 ± 0.29		4.31 (3.31-6.17)				0.88 (0.72-0.95)
		Peak velocity (m/s)	3.23 ± 0.37		3.12 (2.40-4.45)				0.94 (0.85-0.98)
		Avg step rate (steps/s)	4.28 ± 0.29		5.38 (4.13-7.73)				0.46 (0.09-0.76)
		Avg step length (m)	0.65 ± 0.10		6.71 (5.14-9.66)				0.83 (0.62-0.93)
(Nédélec et al., 2013)	Inter-day reliability	Mean speed (m/s)			2.6				0.89
		Peak speed (m/s)			2.2				0.88
(Zois et al., 2013)	Intra-day reliability	Peak velocity (m/s)			3.5				
		Mean velocity (m/s)			4.0				
		Initial acceleration (m/s/s)			12.3				
(Cross et al., 2014)	Intra-day reliability	Peak velocity (m/s)			1.6				0.98
		Contact time - first two steps (ms)			5.6				0.82
		Contact time - at max velocity (ms)			2.8				0.89
		Flight time - first two steps (ms)			9.2				0.90
		Flight time - at max velocity (ms)			4.2				0.97
		Step frequency - first two steps (ms)			4.8				0.87
		Step frequency - at max velocity (ms)			2.1				0.94
		Step length - at max velocity (ms)			2.0				0.99

Note. NMT = non-motorised treadmill; TT = torque treadmill; CV = coefficient of variation; CI = confidence interval: SEM = standard error of measurement; LoA = limits of agreement; ICC = intraclass correlation coefficient; MxSP = maximal speed; Max = maximum; Avg = average

[a] When mean2 data are absent in the table, mean1 data represent the "grand mean" of the study

Table 4. Reliability of kinetic results from NMT and torque treadmill technology (all reliability test results are for NMT unless stated).

					Absolute reliability				Relative reliability
Reference	Reliability	Variables	Mean1 [a]	Mean2	CV (%) (CI)	SEM (CI)	LoA	Ratio LoA	ICC (CI) / r [b]
(Jaskolski et al., 1996)	Inter-day reliability (TT)	Power (W)							0.76-0.94
(Tong et al., 2001)	Intra-day reliability	Max avg horizontal force (N)	192 ± 17	191 ± 16	8.0		1 ± 22	1.01 ×/÷ 1.15	
		Max avg power (W)	900 ±103	896 ± 90	5.5		4 ± 98	1.07 ×/÷ 1.12	
		Max instantaneous horizontal force (N)	427 ± 69	430 ± 69	8.9		4 ± 70	1.01 ×/÷ 1.21	
		Max instantaneous power (W)	2511 ± 579	2562 ± 568	9.3		51 ± 464	1.02 ×/÷ 1.20	
	Inter-day reliability	Max avg horizontal force (N)	198 ± 46	195 ± 15	8.5		4 ± 27	1.02 ×/÷ 1.17	
		Max avg power (W)	900 ± 98	930 ± 109	8.2		30 ± 157	1.03 ×/÷ 1.16	
		Max instantaneous horizontal force (N)	453 ± 65	436 ± 60	9.1		16 ± 84	1.04 ×/÷ 1.19	
		Max instantaneous power (W)	2679 ± 521	2784 ± 564	9.3		105 ± 58	1.04 ×/÷ 1.21	
(Yanagiya et al., 2003)	Inter-day reliability	Mean power output (W)							0.80-0.96
(Yanagiya et al., 2004)	Inter-day reliability	Relative mean power output (W/kg)			6.8				0.941 [b]
(Hughes et al., 2006)	Inter-day reliability (trial 1-2)	AvF (N)	79.6		4.1 (2.4-6.8)	2.32 (1.60-4.24)		1.02 ×/÷ 1.08	
		Percent decrement AvF (%)	6.83		33.7 (19.8-55.9)	1.63 (1.12-2.98)		0.71 ×/÷ 1.99	
	Inter-day reliability (trial 2-3)	AvF (N)	79.4		5.0 (2.8-8.5)	2.78 (1.88-5.33)		0.99 ×/÷ 1.10	
		Percent decrement AvF (%)	6.46		23.9 (13.5-41.1)	1.09 (0.74-2.09)		1.65 ×/÷ 1.78	
	Combined reliability (3 sessions of 6 sprints)	AvF (N)	79.5 ± 4.4		3.9 (2.7-5.5)				
		Percent decrement AvF (%)	6.26 ± 2.65		30.1 (20.7-42.6)				
(Oliver et al., 2006)	Inter-day reliability (all trials)	Peak power output (W)	619		8.32 (6.77-10.81)				
		Mean power output (W)	439		5.41 (4.40-7.03)				
(Lim & Chia, 2007)	Inter-day reliability (TT)	Peak power (W)			1.9	14.02			0.99 [b]
		Mean power (W)			5.8	26.75			0.96 [b]
	Intra-day reliability (TT)	Peak power (W)			4.3	27.04 [c]			0.99 [b]
		Mean power (W)			5.0	21.80 [c]			0.98 [b]
(Sirotic & Coutts, 2008)	Inter-day reliability (trial 1-2)	6 s Mean max power	964.36		9.0 (6.5-17.1)			1.00 ×/÷ 1.27	0.81 (0.41-0.95)
		3 s Mean max power	1029.35		15.6 (11.5-31.5)			0.99 ×/÷ 1.49	0.49 (-0.15-0.84)
	Inter-day reliability (trial 2-3)	6 s Mean max power	965.25		5.4 (3.9-10.0)			1.00 ×/÷ 1.16	0.92 (0.70-0.98)
		3 s Mean max power	1043.75		10.1 (7.3-19.3)			1.04 ×/÷ 1.30	0.79 (0.37-0.94)
(Hopker et al., 2009)	Inter-day reliability (trial 1-2)	Peak horizontal force (N)			17.8 (14.5-23.0)				
		Peak power (W)			20.7 (16.9-26.8)				
		Mean horizontal force (N)			8.1 (6.6-10.5)				
		Mean power (W)			10.9 (8.9-14.1)				
	Inter-day reliability (trial 2-3)	Peak horizontal force (N)			12.2 (10.0-15.8)				
		Peak power (W)			21.1 (17.2-27.3)				

Reference	Reliability	Variables	Mean1 [a]	Mean2	Absolute reliability				Relative reliability
					CV (%) (CI)	SEM (CI)	LoA	Ratio LoA	ICC (CI) / r [b]
		Mean horizontal force (N)			5.9 (4.8-7.6)				
		Mean power (W)			-				
	Inter-day reliability (trial 3-4)	Peak horizontal force (N)			9.4 (7.7-12.1)				
		Peak power (W)			10.1 (8.2-13.1)				
		Mean horizontal force (N)			7.9 (6.4-10.2)				
		Mean power (W)			-				
	Inter-day reliability (trial 2-4)	Peak horizontal force (N)			-				
		Peak power (W)			-				
		Mean horizontal force (N)			-				
		Mean power (W)			7.4 (6.4-8.8)				
	Inter-day Rreliability (all trials)	Peak horizontal force (N)	420.9 ± 87.7						0.47-0.74
		Peak power (W)	1376.8 ± 451.9						0.54-0.83
		Mean horizontal force (N)	147.2 ± 24.7						0.79-0.91
		Mean power (W)	514.9 ± 164.5						0.83-0.93
(Morin et al., 2010)	Intra-day reliability (TT)	Peak relative power (W/kg)	22.2 ± 2.01	22.9 ± 2.00					0.90 / 0.94 [b]
(Sweeney et al., 2010)	Intra-day reliability	Peak power output (W)							0.92 [b]
		Mean power output (W)							0.99 [b]
(Serpiello et al., 2011)	Intra-day reliability	Peak power output (W)			10.8				
		Mean power output (W)			4.7				
(Nédélec et al., 2012)	Inter-day reliability	Peak power output (W)	2231 ± 267		4.1 (2.8-7.3)				0.91 (0.70-0.98)
		Mean power output (W)	1903 ± 228		1.4 (1.0-2.6)				0.99 (0.96-1.00)
(Rumpf, 2012)	Inter-day reliability (all trials)	Avg power (W)	300 ± 41.0		5.43 (4.17-7.80)				0.86 (0.69-0.95)
		Peak power (W)	558 ± 86.8		6.99 (5.35-10.1)				0.83 (0.63-0.94)
		Avg horizontal force (N)	108 ± 13.2		2.37 (1.81-3.37)				0.45 (0.07-0.75)
		Peak horizontal force (N)	392 ± 63.1		5.16 (3.95-7.39)				0.70 (0.40-0.88)
		Avg vertical force (N)	328 ± 49.0		3.71 (2.85-5.30)				0.26 (-0.11-0.63)
		Peak vertical force (N)	859 ± 160		2.47 (1.90-3.52)				0.71 (0.43-0.88)
(Cross et al., 2014)	Intra-day reliability	Peak vertical force - first two steps (N)			3.1				0.98
		Peak vertical force - at max velocity (N)			1.8				0.99
		Mean vertical force - first two steps (N)			1.6				0.99
		Mean vertical force - at max velocity (N)			1.5				1.00
		Peak horizontal force - first two steps (N)			5.8				0.89
		Peak horizontal force - max velocity (N)			6.5				0.87
		Peak power output - first two steps (N)			6.1				0.92
		Peak power output - at max velocity (N)			6.6				0.94

NMT = non-motorised treadmill; TT = torque treadmill; CV = coefficient of variation; CI = confidence interval; SEM = standard error of measurement; LoA = limits of agreement; ICC = intraclass correlation coefficient; r = correlation coefficient; Max = maximum; Avg = average; AvF = average mean horizontal force. [a] When mean2 data are absent in the table, mean1 data represent the "grand mean" of the study; [b] correlation coefficient (r); [c] technical error of measurement (TEM) not standard error of measurement (SEM)

Table 5. Validity of kinematic and kinetic results from NMT and torque treadmill technology.

Reference	Validity	Variables	Mean1 (NMT/TT)	Mean2 (Over-ground)	Absolute reliability			Relative reliability
					CV (%) (CI)	LoA	Ratio LoA	r
(Chelly & Denis, 2001)	Concurrent validity (TT vs radar)	Max speed (m/s)	6.1 ± 0.4	8.5 ± 0.3				0.73
(Chia & Lim, 2008)	Concurrent validity (TT vs WAnT)	Peak power (W) (NMT vs WAnT)	647.1 ± 176.4	597.0 ± 146.0 [a]			1.08 x/÷ 1.04	0.89
		Mean power (W) (NMT vs WAnT)	509.0 ± 130.7	548.7 ± 131.3 [a]			0.93 x/÷ 1.05	0.83
(Hopker et al., 2009)	Concurrent validity (NMT vs photocells)	Time to 20 m (s) (Trial 1)	6.7 ± 1.4	3.5 ± 0.5 [b]				
		Time to 20 m (s) (Trial 2)	5.9 ± 1.0	3.5 ± 0.5 [b]				
		Time to 20 m (s) (Trial 3)	5.9 ± 1.0	3.5 ± 0.5 [b]				
		Time to 20 m (s) (Trial 4)	5.8 ± 1.0	3.5 ± 0.5 [b]				
(Morin et al., 2011)	Concurrent validity (TT vs radar)	Max speed (m/s)	6.61 ± 0.45	8.79 ± 0.59 [c]				-
		Max speed - V0 vs radar (m/s)	8.53 ± 0.84	8.79 ± 0.59 [c]				0.90
(Morin & Seve, 2011)	Concurrent validity (TT vs radar)	Time to 100 m (s)	17.0 ± 1.01	13.3 ± 0.71 [c]				0.81
		Mean 100 m speed (m/s)	5.90 ± 0.36	7.57 ± 0.42 [c]				0.82
		Max speed (m/s)	6.90 ± 0.39	8.84 ± 0.51 [c]				0.89
		Time to reach max speed (s)	5.12 ± 1.05	6.21 ± 1.43 [c]				-0.01
		Acceleration constant τ1 (s)	1.60 ± 0.20	1.94 ± 0.38 [c]				0.63
		Deceleration constant τ2 (s)	69.7 ± 17.2	73.4 ± 26.8 [c]				0.76
(Highton et al., 2012)	Concurrent validity (Day 1) (NMT vs photocells)	Time to 10 m (s)	2.39 ± 0.17	1.70 ± 0.20 [b]	23.9	-0.02 ± 0.33	0.71 ×/÷ 1.26	0.43
		Time to 20 m (s)	4.23 ± 0.26	3.01 ± 0.22 [b]	23.8	-0.06 ± 0.31	0.71 ×/÷ 1.14	0.54
		Time to 30 m (s)	6.10 ± 0.36	4.23 ± 0.25 [b]	25.7	-0.07 ± 0.39	0.69 ×/÷ 1.11	0.58
		Time 10-20 m (s)	1.80 ± 0.11	1.30 ± 0.05 [b]	22.8	-0.04 ± 0.16	0.72 ×/÷ 1.11	0.50
		Time 20-30 m (s)	1.83 ± 0.11	1.20 ± 0.06 [b]	29.7	-0.01 ± 0.22	0.65 ×/÷ 1.08	0.67
		Mean speed (m/s)	4.94 ± 0.27	7.02 ± 0.42 [b]	25.5	0.03 ± 0.27	0.70 ×/÷ 1.12	0.58
	Concurrent validity (Day 2) (NMT vs photocells)	Time to 10 m (s)	2.30 ± 0.22	1.70 ± 0.20 [b]	21.2	-0.60 ± 0.48	0.74 ×/÷ 1.26	0.44
		Time to 20 m (s)	4.13 ± 0.25	3.01 ± 0.22 [b]	22.1	-1.12 ± 0.45	0.73 ×/÷ 1.12	0.66
		Time to 30 m (s)	6.00 ± 0.30	4.23 ± 0.25 [b]	24.5	-1.77 ± 0.47	0.70 ×/÷ 1.09	0.80
		Time 10-20 m (s)	1.82 ± 0.11	1.30 ± 0.05 [b]	23.7	-0.52 ± 0.16	0.71 ×/÷ 1.11	0.30
		Time 20-30 m (s)	1.83 ± 0.14	1.20 ± 0.06 [b]	29.4	-0.63 ± 0.15	0.65 ×/÷ 1.08	0.48
		Mean speed (m/s)	5.02 ± 0.25	7.02 ± 0.42 [b]	24.5	2.01 ± 0.71	0.71 ×/÷ 1.12	0.60
(Takai et al., 2013)	Concurrent validity (NMT vs over-ground)	Velocity (m/s)						0.87

NMT = non-motorised treadmill; TT = torque treadmill; CV = coefficient of variation; CI = confidence interval; LoA = limits of agreement; r = correlation coefficient; WAnT = Wingate anaerobic test on bicycle ergometer; V*0* = theoretical maximum velocity; Max = maximum

[a] Wingate anaerobic cycle test results; [b] Photocell data; [c] Radar data

Short sprints (≤ 30 m) on a NMT resulted in 28-67% slower mean speed and split times compared to over-ground sprinting (Highton et al., 2012; Hopker et al., 2009). However, based on predominantly large to very large correlations (r = 0.54-0.80) between over-ground and NMT sprinting performance for mean speed and time to 20-30 m, Highton et al. (2012) concluded that subjects that are relatively fast over-ground would also tend to be relatively fast on the NMT, especially for distances greater than 20 m. The corresponding absolute reliability findings were poor however, with very high CV results (21-30%) and RLoA results indicating a large degree of bias (0.65-0.74) and a range of agreement ratios (×/÷ 1.08-1.26) between the NMT and over-ground results even for distances greater than 20 m. The full range of correlation coefficients reported (r = 0.30-0.80) also mean that the NMT results only explain 9-64% of the variance in measurements of speed and time to cover various distances up to 30 m during over-ground sprinting (Highton et al., 2012).

The main reason suggested for the reduced sprint performance consistently observed on the NMT compared to over-ground sprinting is the high intrinsic resistance of the treadmill belt (Highton et al., 2012; Lakomy, 1987). The inertia of the moving mass of the treadmill is also different compared to the over-ground condition. While sprinting at maximum velocity over-ground the net F_h will approach zero. In contrast, when sprinting on a NMT this inertial characteristic will not be achieved due to the additional retarding forces acting on the runner compared to sprinting over-ground. The torque motor of a torque treadmill should theoretically enable more valid sprinting speeds to be achieved. The correlations are typically large between torque treadmill and over-ground kinematic variables (r ≥ 0.63; excluding time to reach maximum speed), but there have still been reports of approximately 20-28% lower maximum speeds on a torque treadmill compared to over-ground sprinting (Chelly & Denis, 2001; Morin et al., 2011; Morin & Seve, 2011). Morin et al. (2011) calculated a theoretical treadmill top speed as the x-axis intercept (V0) from the extrapolation of the linear relationship between the mean *RF* results and the horizontal speed measured on the TT. The V0 values were on average only about 3% slower than the actual top speeds and were very strongly correlated (r = 0.90) with top speeds measured during over-ground sprinting. Additionally, Chelly and Denis (2001) reported that average horizontal power measured on the torque treadmill was strongly correlated with maximal over-ground sprint velocity (r = 0.73) and when expressed relative to body weight, average horizontal power was also strongly correlated with initial acceleration (r = 0.80).

The study of concurrent validity between kinetic measurements made on a torque treadmill and kinetic measurements made during over-ground sprinting have been very limited. As explained in the Radar and Laser Technology section of this review, F_h measurements on a torque treadmill were approximately 31% higher (i.e. ~ 12% of body weight) than F_h measurements made with a radar gun during a 100 m over-ground sprint (Morin et al., 2011; Morin & Seve, 2011). No studies to date have compared kinetic measurements made on a NMT or torque treadmill with kinetic measurements made on imbedded force plates during over-ground sprinting. There have also been no reports on the validity of ground contact time, flight time, stride frequency and stride length measured on a NMT/torque treadmill during short sprint accelerations.

Discussion

Key Findings

This systematic review of the literature has determined that while acceptable intra-day reliability (Debaere et al., 2013; Delecluse et al., 2005; di Prampero et al., 2005; Ferro et al., 2012; Samozino et al., 2015), inter-day reliability (Ferro et al., 2012) and validity (Berthoin et al., 2001; Bezodis et al., 2012; Chelly & Denis, 2001; di Prampero et al., 2005; Ferro et al., 2012; Morin et al., 2006; Samozino et al., 2015) of radar and laser technology has been established for measuring speed, limitations exist in the validity of the results obtained in the initial 5 m of a sprint from a standing start (Bezodis et al., 2012). These limitations appear to be due to the change in sprinting posture (i.e. increasingly less forward lean) during the first few steps (Bezodis et al., 2012), however the contribution of error introduced through post-processing techniques such as those used to identify the exact start of the sprint cannot be ruled out. No comparison has been reported to date of the reliability of a series of distances (e.g. 5, 10, 20, 30 m) measured with radar or laser technology. Despite this, excellent concurrent validity results were reported for sprint split times (10-100 m) measured with radar/laser compared to photoelectric cells (Berthoin et al., 2001; di Prampero et al., 2005; Morin et al., 2006).

Various start positions have been trialed in order to improve sprint test reliability when using photoelectric cells (Grant M. Duthie et al., 2006). Sprint testing protocols typically utilise a start position that is up to 50 cm behind the first timing gate in order to avoid a false signal resulting in a premature timing start due to the forward lean of the subject (Winter, Jones, Davidson, Bromley, & Mercer, 2007). While Bezodis et al. (2012) reported unacceptable error with laser compared to video results during the initial 5 m of a sprint, a benefit of radar and laser technology is that a horizontal velocity limit (e.g. 1 m/s) can be set to signify the start of a trial. It is anticipated that this method may result in increased reliability and reduced technical error of measurement when using radar and laser devices compared to photoelectric cells.

Acceptable intra-day reliability was reported for radar-derived summary values for the mechanical capabilities of the lower limbs (i.e. F0, V0, Pmax and S_{Fv}) within a sample of sprinters (Samozino et al., 2015). Reliability was also acceptable for laser-derived summary values within a population of young (14.1 ± 2.4 years) soccer players, except the relative reliability of F0 (Buchheit et al., 2014). It seems likely that there could be increased movement variability at the start of a sprint within a population of young team sport athletes compared to high-level sprinters. Further research is required to determine the inter-day test-retest reliability of summary values for the mechanical capabilities of the lower limbs derived from radar and laser devices.

Samozino et al. (Samozino et al., 2013; Samozino et al., 2015) recently reported strong support for the validity of F0, V0 and Pmax measured using a series of five split times between 10 m and 40 m, with 2-5% absolute bias compared to kinetic results simultaneously recorded with embedded force platforms. These results were not included in the current study due to the use of photoelectric cells instead of radar or laser technology. Rabita et al. (2015) also analysed multiple sprints over force platforms to reconstruct a virtual 40 m sprint. These authors validated the shape of the linear F_h-velocity and quadratic horizontal power-velocity curves during over-ground sprinting (Rabita et al., 2015; Samozino et al., 2015). Samozino et al. (2015) also reported acceptable agreement between kinetic data (including F0, V0, Pmax, S_{Fv} and D_{RF}) from radar and force platforms. Future research in this area should more fully explore the concurrent validity of the results derived from radar or laser.

Unacceptable levels of reliability for power output measured on a NMT were reported by some authors (Hopker et al., 2009; Serpiello et al., 2011; Sirotic & Coutts, 2008). These results may be expected as power output is the product of F_h and speed and therefore includes variability from the measures of both of these inputs. Based on reported reliability results it has previously been suggested that the detection of very small changes in sprint performance (e.g. ~1%) using a NMT would require an impracticably large sample size (Sirotic & Coutts, 2008; Tong et al., 2001). However, the results of the current study indicate that there are a number of techniques that can be used to improve reliability even for very short maximal acceleration sprints on a NMT or TT:

1. *Familiarisation:* Two familiarisation sessions, or 10-20 familiarisation trials should be sufficient to ensure no further learning effect (Morin et al., 2010; Sirotic & Coutts, 2008). Hopker et al. (Hopker et al., 2009) suggested that at least three familiarisation sessions may be required, however this was based upon a very low volume of sprinting during each session (i.e. only one maximal sprint per session).

2. *Sampling Rate:* A sampling rate of ≥ 200 Hz should be used. All authors that utilised a sampling rate of ≥ 200 Hz have reported acceptable levels of reliability (Cross et al., 2014; Morin et al., 2011; Morin et al., 2010; Yanagiya et al., 2003; Yanagiya et al., 2004), except when a population of children was studied (Rumpf, 2012).

3. *Start position:* Previous start protocols have included stationary (Chelly & Denis, 2001; Highton et al., 2012; Jaskolski et al., 1996; Sirotic & Coutts, 2008) or rolling (walking/jogging) start positions (Chia & Lim, 2008; Hopker et al., 2009; Lim & Chia, 2007; Tong et al., 2001). The "blocked" start technique used in several recent studies (Cross et al., 2014; Morin et al., 2011; Morin et al., 2010; Morin & Seve, 2011) appears to be the most reliable and relevant method for testing sprint acceleration. The "blocked" start involves an experimenter manually stopping any belt movement prior to the sprint start by placing a foot on the back of the belt surface. This allows the subject to assume a typical standing sprint

start position with their body leaning forward and one foot placed forward, rather than the more upright position that would otherwise be necessary on a NMT or TT.

4. *Multiple sprints:* Results may be averaged over multiple sprints to improve reliability (Hughes et al., 2006; Nédélec et al., 2012).

5. *Analyse steps rather than time periods*: High sampling rates enable data to be selected and analysed from each ground contact. Thus the GRF results correspond to specific muscular events during each ground contact (Morin et al., 2010). This method has resulted in consistently high reliability results (Cross et al., 2014; Morin et al., 2010; Yanagiya et al., 2003; Yanagiya et al., 2004).

There has been no assessment of the validity of F_h, F_v and F_{tot} measured during sprinting on a NMT or TT. In the earliest assessment of NMT validity, one long (30 s) sprint on a NMT was characterised by significantly shorter stride lengths as well as lower peak and mean speed by 21.4% and 24.8% respectively compared to over-ground sprinting assessed with high-speed video (Lakomy, 1987). NMT sprinting also resulted in a 13.1 ± 7.6° increase in forward lean of the body compared to sprinting on a motorised treadmill. While there have been no reports to date regarding the validity of many kinematic measurements during short accelerations on a NMT/torque treadmill, a comparison of similar studies of sprinting on a NMT (Cross et al., 2014) and over-ground (Bushnell & Hunter, 2007; Lockie et al., 2014; Lockie et al., 2012; Mann, 2011; Rabita et al., 2015) tends to suggest that longer contact times and shorter flight times and stride lengths would be expected on a NMT compared to over-ground sprinting. It may be theorised that these differences in sprint technique would mean that stronger, F-dom athletes would tend to perform relatively better than v-dom athletes on a NMT/torque treadmill compared to over-ground sprinting.

The findings from short sprint efforts summarised in the current review show that sprinting times and speeds were 20-28% slower on a TT, 28-67% slower on a NMT, and that only 9-64% of the variance in measurements of speed and time (≤ 30 m) was explained by results from a NMT compared to over-ground sprinting (Chelly & Denis, 2001; Highton et al., 2012; Hopker et al., 2009; Morin et al., 2011; Morin & Seve, 2011). Given that NMT and photoelectric cells purport to measure the same qualities, the unexplained variance of up to 91% is problematic and should be understood before implementing NMT analysis with athletes. This is particularly so when the findings of Weyand, Sandell, Prime, and Bundle (2010) are considered, which suggest that humans are typically not force limited in sprint-running, but rather we are limited by the time available for force application. While further research is required to establish the validity of certain kinematic and kinetic variables, the weight of the current findings tend to suggest that NMT results should be used mainly for intra-individual comparisons in performance with different acute and chronic training strategies, for comparisons at different phases in the training cycle, and/or for comparisons of left and right leg balance during sprinting.

Limitations

A limitation of this summary of reliability and validity results from multiple studies is that the subject populations, testing devices and testing protocols were different across the studies, making definitive conclusions problematic. There was a sex bias within the included studies with 21 of the 33 studies testing exclusively male participants. The majority of studies involved reasonably heterogeneous populations, which may result in a bias towards higher correlations (Hopkins, 2000). Additionally, 18 out of 33 studies had a sample size of only 12 or fewer participants. A sufficient sample size is critical for controlling type I and type II error (Nevill, Holder, & Cooper, 2007). Relative validity and reliability results are also particularly dependent on the number of subjects and the heterogeneity of the population testing (Hopkins, 2000).

The body position of the athlete is crucial for achieving higher accelerations (Kugler & Janshen, 2010; Mann, 2011). Radar, laser, NMT and torque treadmill technologies all enable a testing option for profiling F_h against velocity during sprinting, however no assessment of the specific technical proficiency of the sprinter is inherent with these tools. The values for F_h and horizontal power derived from radar, laser, NMT and torque treadmill are related to both the force generating capacity of the athlete as well as the ability of the athlete to achieve sufficient forward lean during acceleration so that the force applied in the horizontal direction is optimised. Practitioners should understand that improvements in F_h, horizontal power and speed can be achieved by increasing the force-generating capacity of the athlete and/or by improving the technical proficiency of the athlete (Kugler & Janshen, 2010; Morin et al., 2011).

Limitations of Radar and Laser Technology

Various techniques are used to smooth the raw speed data obtained from radar and laser technology, however di Prampero et al. (2005) warned that this may lead to a large smoothing of the natural speed fluctuations that occur during each sprinting step. Additionally, radar and laser devices estimate the displacement of the subject's COM based on the displacement of the subject's lower back. At the start of the sprint the COM moves in relation to the lower back (Bezodis et al., 2012) and also the COM rises while the radar or laser tripod height does not change (di Prampero et al., 2005). This limitation will only impact on the data during the first few steps of the sprint.

While F_h can be derived from radar and laser results, F_v cannot be calculated using these technologies. However, F_v can be estimated as being equivalent to body weight over the time period of one ground contact and the subsequent flight time (Samozino et al., 2015). This possibility enables the calculation of RF in a similar manner to that discussed above (NMT and torque treadmill technology section) using torque treadmill technology. Samozino et al. (2015) used split times from photoelectric cells to calculate the slope of the RF-speed relationship (D_{RF}) and reported acceptable reliability (CV = 4.0 ± 2.8%; SEM = 4.9%) and validity of the method (absolute bias = 6.0 ± 5.7%).

Limitations impacting on the practical application of radar and laser technology include that the units can only measure sprinting in a straight line towards or away from the device, so cannot be used for many agility tests with direction changes. The technology would however be suitable for assessing speed, acceleration and deceleration during agility tests that include a 180 ° direction change such as the 505 change of direction speed test (Draper & Lancaster, 1985). Instead of a total time to complete the 505 change of direction test measured with photoelectric cells, radar and laser technology would enable splitting such a test into three sections: acceleration, deceleration and re-acceleration. This application would only be suitable if split times from radar and laser devices are confirmed to have acceptable reliability for very short sprints (i.e. 5 m).

Additionally, while photoelectric cells reliably provide instant feedback to subjects on their split-time performance, radar and laser devices currently require substantial post-processing before split-times and other variables can be reported. This limitation is particularly relevant when considering suitable technology for using within sprint training sessions where instant feedback may be required.

Limitations of NMT and Torque Treadmill Technology

The main limitation of NMT and torque treadmill technology is the differences in treadmill sprinting performance when compared to over-ground sprinting. Maximal sprinting speeds on the NMT/torque treadmill are typically 20-67% slower compared to over-ground sprinting (Chelly & Denis, 2001; Highton et al., 2012; Hopker et al., 2009; Lakomy, 1987; Morin et al., 2011; Morin & Seve, 2011), with lighter subjects being at an added disadvantage compared to heavier subjects (Lakomy, 1987). While Lakomy (1987) found that the F_h required to maintain a constant sub-maximal speed on the NMT was increased with the body weight of the subject, lighter subjects were still at a disadvantage as more F_h relative to body weight is required at a given speed compared to heavier subjects. Another limitation of the majority of NMT/torque treadmill models is that F_h is not measured at the point of foot contact, but instead is indirectly measured through a tether attached to the horizontal load cell behind the subject or through a load cell on the handlebar of the treadmill. Additional errors in F_h assessment will result if the tether is not very rigid or is not maintained exactly horizontal during the sprint test (Lakomy, 1987).

Comparisons between NMT/torque treadmill studies are complicated due to the range of different treadmill specifications and models, and occasionally torque treadmill being mistakenly referred to as NMT. Testing protocol differences, such as starting position and post-processing treatment of the data, also make comparisons and NMT/torque treadmill study generalisations difficult. Based on the results to date it would seem that torque treadmills that enable measurement of both F_h and F_v at the point of foot contact should be preferred over NMT due to: (i) the torque motor of the torque treadmill accounting to some extent for the body weight of the subject and resulting in speeds that more closely match over-ground running speeds; and (ii) the inherent limitations of the indirect measurement of F_h.

Future Research

Future research is required to fully assess the intra-day and inter-day test-retest reliability of the radar and laser technology, as well as the validity of the measurements of F_h and power. Specifically, the reliability of short sprint split times, deceleration and the inter-day reliability of additional variables of interest such as F0, V0, S_{Fv} and Pmax should be quantified. A thorough analysis of the validity of the devices is also required. Reliability studies should focus on the 1-3 s accelerations typical in team sports as well as longer sprint efforts ≥ 4 s to include an acceleration assessment right up to maximal velocity.

To better understand the efficacy of GRF measured using a NMT, future research should compare NMT sprint results with over-ground sprinting assessed with radar or laser technology, or over tracks with embedded force platforms. Research utilising NMT/torque treadmill technology should focus on the analysis of foot contacts rather than arbitrary time windows for the assessment of kinetic and kinematic data. Sprint acceleration may be split into the start (first two steps) and the transition (steps 3-10) (Mann, 2011). NMT/torque treadmill technology should be used to analyse in more detail the kinematic and kinetic variables associated with the first 10 steps of acceleration. Analysis of bilateral differences in step characteristics over this acceleration phase on a NMT or torque treadmill has been absent in the literature to date, but this comparison may provide important insight into any lingering adverse effects of prior injuries or may identify individuals at increased risk of future injury (Brughelli et al., 2010). Theoretical maximum horizontal velocity (V0) on a NMT should also be compared with maximum speed over-ground, as has been performed with the TT.

Valid and reliable sprint acceleration profiling of adolescents is important within contexts such as long-term athlete development programs. Unacceptable reliability of certain variables measured with NMT and laser was reported in the literature within an adolescent population (Buchheit et al., 2014; Rumpf, 2012). Future research should address these issues and establish guidelines for the reliable analysis of adolescent sprinting, including F_h profiling.

Finally, future research with radar, laser, NMT and torque treadmill technology should analyse force-velocity and power-velocity profiles from a range of team sport athletes during maximal effort accelerations up to s_{max}. A better understanding of the relationship between the key output variables (F0, V0, S_{Fv}, Pmax, RF, D_{RF} and bilateral leg balance) and sprint performance would provide direction for the individualisation of speed training programming. The mechanical capabilities of the lower limbs may be summarised by three variables: F0, V0 and Pmax; and relatively force-dominant (F-dom) and relatively velocity-dominant (v-dom) individuals can be identified from the S_{Fv} results (Samozino et al., 2012). Relatively F-dom individuals are identified by a lower (steeper) S_{Fv} indicating relatively high force capabilities compared with velocity capabilities; while relatively v-dom individuals are identified by a higher (flatter) S_{Fv} indicating relatively high velocity capabilities compared with force capabilities. Morin et al. (2012) compared linear force-velocity relationships determined from a 6 s sprint on a TT, with over-ground sprint performance measured using a radar device. Both 4 s and 100 m over-ground sprint performance was significantly correlated with V0 ($r = 0.735 - 0.841$), but not with F0 ($r = 0.432 - 0.560$). The authors concluded that higher acceleration and 100 m performance was associated with a more "velocity-oriented" force-velocity profile. Considering maximum F_h values occur at the start of acceleration, it may be hypothesised that F0 would be more related to early acceleration performance (e.g. 1-2 s distance), however d_{4sec} was the only acceleration measure reported in this study. The power-velocity profile, Pmax and S_{Fv} were also not quantified in this study.

Conclusions

Radar, laser, NMT and torque treadmill technologies enable the high-frequency measurement of sprint acceleration performance as well as some of the kinematic and kinetic determinants of sprinting speed including F_h.

Radar and laser technology are generally valid and reliable methods for measuring sprinting speed, although reduced validity is associated with the first few metres of an acceleration sprint due to the movement of the lower back in relation to the COM as the sprinting posture becomes more upright. Acceptable reliability of the measurement of short sprint accelerations using NMT/torque treadmill can be achieved with suitable testing protocols, including: sufficient familiarisation, a high sampling rate (≥ 200 Hz), a "blocked" start position and analysis of the discrete moments of ground contact. Large decrements in top sprinting speeds on NMT/torque treadmill compared to over-ground performance are mitigated to some extent by the torque motor of a torque treadmill. Torque treadmill models that also enable the measurement of F_h at the point of foot contact should be preferred over the indirect measurement of F_h. Further research is required to assess the validity of kinetic measures from short sprints on NMT and TT. The focus of this systematic literature review was sprint acceleration profiling for team sport athletes, but the conclusions are also relevant for other athletes (e.g. track sprinters) for whom sprint acceleration ability is a key determinant of sport performance.

CHAPTER 3

RELIABILITY OF HORIZONTAL FORCE-VELOCITY-POWER PROFILING DURING SHORT SPRINT-RUNNING ACCELERATIONS USING RADAR TECHNOLOGY

This paper comprises the following paper published in *Sports Biomechanics*:

Simperingham, K. D., Cronin, J. B., Pearson, S. N. & Ross, A. (2019). Reliability of horizontal force-velocity-power profiling during short sprint-running accelerations using radar technology. *Sports Biomechanics*, *18*(1), 88-99.

Prelude

The utility, reliability and validity of radar, laser, NMT and torque treadmill devices for sprint acceleration profiling were summarised in the systematic literature review in the previous chapter. Generally acceptable validity (r = 0.87-0.99; absolute bias 3-7%), intra-day reliability (CV ≤ 9.5%; ICC/r ≥ 0.84) and inter-day reliability (ICC ≥ 0.72) were reported for data from radar and laser. However, low intra-day reliability was reported for F0 (ICC = 0.64) in adolescent athletes and low validity was reported for velocity during the initial 5 m of a sprint acceleration (bias up to 0.41 m/s) measured with a laser device. Recommendations for future research in this area included quantifying the reliability of short sprint split times and the reliability of the variables that were proposed to summarise the mechanical capabilities of the lower limbs (F0, V0 and Pmax) and S_{Fv}. The aim of the following chapter was to address these points by assessing the intra-day and inter-day reliability of radar-derived profiling data from 30 m sprints within a population of team sport athletes. Reliability was interpreted as acceptable in the previous chapter for an ICC ≥ 0.70 and a CV ≤ 10%, however an increased relative reliability threshold was set in the following two chapters, so average reliability was interpreted as acceptable for an ICC ≥ 0.75 and a CV ≤ 10%.

Introduction

Sprint-running speed is an important physical quality for a range of sports, with short 10-20 m or 2-3 s sprints being particularly prevalent during field-based team sport games (Spencer et al., 2005). Reliable measurement of the sprint acceleration phase is therefore critical in order to be able to identify small but practically important changes in performance over time (Simperingham, Cronin, & Ross, 2016).

Photoelectric cells are commonly used to measure sprint acceleration performance with high reliability for sprints as short as 10 m (coefficient of variation [CV] approximately 1%, typical error approximately 0.02s) (Cronin & Templeton, 2008; Grant M. Duthie et al., 2006). Recently, radar and laser technology have been used more frequently to assess sprint performance with the added benefit of high frequency sampling of time-series horizontal velocity being used to calculate instantaneous horizontal force and power as well as displacement (Bezodis et al., 2012; Buchheit et al., 2014; Cross et al., 2015; di Prampero et al., 2005; Ferro et al., 2012; Morin et al., 2011; Morin et al., 2006; Samozino et al., 2015). Radar and laser devices are typically positioned directly behind the participant and infer centre of mass (COM) velocity by measuring the movement speed of the back or lumbar point on the individual where the device is focused (di Prampero et al., 2005; Morin et al., 2006). Radar devices measure the change in frequency of the radio waves that bounce off the participant, while laser devices measure the time delay of pulsed infrared light that is reflected off the participant.

Recently, simulations of human running were used to demonstrate the critical limiting role of the force-velocity relationship on maximum sprinting speed (Miller, Umberger, & Caldwell, 2012). Maximal sprint-running as well as maximal jump and cycle performance may be illustrated by inverse linear force-velocity and quadratic power-velocity relationships (Martin, Wagner, & Coyle, 1997; Morin et al., 2010; Samozino et al., 2012). These relationships describe the mechanical capabilities of the body and may be summarised by three variables that can be calculated from velocity measured with radar or laser devices during sprint-running: F0, V0 and Pmax (Figure 6) (Rabita et al., 2015; Samozino et al., 2010; Samozino et al., 2015; Samozino et al., 2012). These three variables are interrelated such that Pmax occurs at an optimal level of horizontal force (0.5*F0) and at an optimal velocity (0.5* V0). The slope of the force-velocity relationship (S_{Fv}) can be calculated from the intercepts of the force-velocity curve (i.e. S_{Fv} = -F0/V0) and may provide a means of comparison between individuals independent of their power capabilities (Samozino et al., 2012). Force-dominant individuals are identified by a lower (steeper) negative S_{Fv} indicating relatively high force capabilities compared with velocity capabilities. Conversely, velocity-dominant individuals are identified by a higher (flatter) negative S_{Fv} indicating relatively high velocity capabilities compared with force capabilities.

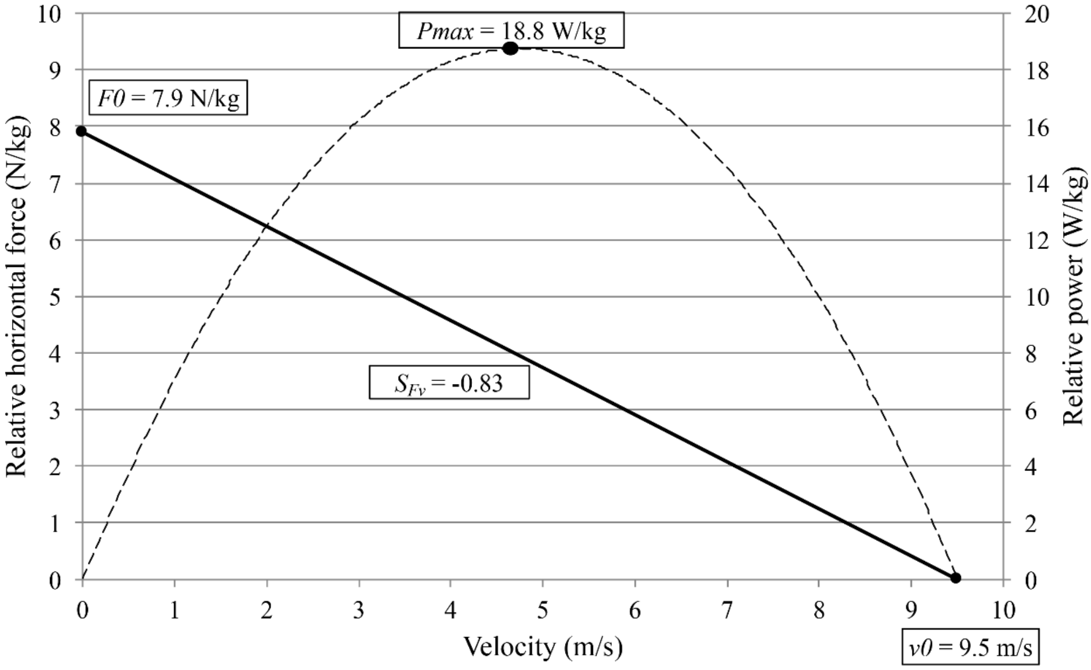

Figure 6. Inverse linear force-velocity and quadratic power-velocity relationships for an individual with the following physical characteristics: theoretical maximum horizontal force (F0) = 7.9 N/kg; theoretical maximum velocity (V0) = 9.5 m/s; maximum power output (Pmax) = 18.8 W/kg; and slope of the force-velocity profile (S_{Fv}) = -0.83 N/m/s/kg.

Measurements of acceleration and sprinting speed over a range of distances up to 100 m using radar or laser technology have been shown to be characterised by acceptable intra-day (CV ≤ 9.5%; systematic error (bias) ≤ 4.1%; intraclass correlation coefficient [ICC] or correlation coefficient ≥ 0.84) and at least moderate inter-day (ICC ≥ 0.72; systematic error (bias) ≤ 6%) reliability (Debaere et al., 2013; Delecluse et al., 2005; di Prampero et al., 2005; Ferro et al., 2012; Simperingham, Cronin, & Ross, 2016). However, the reliability of measures of time to complete a range of distances between 2 m and 30 m has not been reported in the literature. Acceptable intra-day reliability was reported for V0, Pmax, Pmax relative to body mass ($Pmax_{rel}$) and S_{Fv} derived from 40-50 m sprints using radar and laser (CV = 1.1-8.9%; ICC = 0.87-0.97) (Buchheit et al., 2014; Samozino et al., 2015). F0 or F0 relative to body mass ($F0_{rel}$) had good absolute reliability (CV = 2.9-7.8%), but only moderate relative reliability (ICC = 0.64) (Buchheit et al., 2014; Samozino et al., 2015). An assessment of the inter-day reliability of kinetic measures derived from radar or laser is absent in the literature to date. The aim of this study therefore was to determine the intra-day and inter-day reliability of radar-derived kinematic and kinetic measurements of short (≤ 30 m) sprint-running acceleration performance. This aim involves assessing the applied/practical reliability of the testing, which includes both potential variability in the methods used (instrument and analytical), along with athlete biological variations. Given the established reliability of photoelectric cells for measuring sprint acceleration performance (Cronin & Templeton, 2008; Grant M. Duthie et al., 2006), and the very strong agreement between sprint results using radar and photoelectric cells (di Prampero et al., 2005; Morin et al., 2006), it was hypothesised that all radar-derived measures would have acceptable intra-day and inter-day reliability (ICC ≥ 0.75 and CV ≤ 10%).

Methods

This study involved an assessment of the variability of 30 m sprint performance measured with a radar device across three sprints during one session (intra-day analysis) and across four identical testing sessions (inter-day analysis). To control the testing conditions as much as possible, all testing sessions for each participant were performed on the same day of the week, at approximately the same time of the day and on an indoor running track. Testing sessions were repeated at weekly intervals unless illness or minor injury required that an additional week of rest was required. Participants were requested to avoid 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. Absolute reliability of the kinematic and kinetic outcome variables was examined by calculating the typical error of measurement expressed as a CV and relative reliability was examined with the ICC (Hopkins, 2000, 2015).

Participants

Twenty-seven amateur club or provincial age-group representative male rugby union players volunteered to participate in this study (age 18.6 ± 0.6 years; body mass 97.2 ± 20.4 kg; height 180.0 ± 6.4 cm). All participants completed at least one testing session (intra-day analysis), while nine participants completed all four testing sessions for the inter-day analysis (age 18.8 ± 0.4 years; body mass 100.0 ± 20.0 kg; height 177.5 ± 4.8 cm). All discomforts and risks associated with the study were explained prior to participants providing their written informed consent to participate. The study had full ethical approval from the Institutional Ethics Committee.

Procedures

Participants reported to the indoor track in athletic clothing and wearing running shoes. Height and body mass were recorded without shoes. A 15-minute standardised warm-up was completed on an indoor track (including jogging, sprint drills, dynamic stretching and build-up sprints of increasing intensity up to maximal effort). There was then a period of five minutes of passive rest prior to each of the three maximal effort 30 m sprint trials.

The radar device (Stalker ATS II, Texas, USA) had a sampling rate of 47 Hz and was positioned 10 m directly behind the start line on a tripod set at 1 m above ground to approximately align with the centre of mass of the sprinting participants (Morin et al., 2006). Participants were required to start from a stationary split stance position with one foot just behind the start line. Once participants were in the start position, radar data capture was started and participants could begin sprinting at any time (i.e. running times do not include a reaction time). No false step was allowed at the start and participants were instructed to run maximally past a marker that was positioned 30 m from the start.

Instantaneous horizontal velocity was measured continuously with the radar device, which was connected to a laptop running Stalker ATS SystemTM software (Version 5.0.2.1, Applied Concepts, Inc., Texas, USA) for data acquisition. The raw data files were manually processed in the commercially-available software system by: (i) deleting all data recorded prior to the start and after the finish of each sprint; (ii) nominating all trials to be 'acceleration runs' thereby forcing the start of the velocity-time curve through the zero point; and, (iii) manually removing unexpected high and low data points on the velocity-time curve that were likely caused by segmental movements of the participants while sprinting (Figure 7). High and low data points were manually identified (no acceleration threshold was used) and all trials were analysed by the same person to avoid inter-observer differences. The processed data file for each trial together with the height and body mass of each participant was then imported into a custom-made LabView (Version 13.0, National Instruments Corporation, Texas, USA) program that was used to calculate all outcome variables (F0, V0, Pmax, S_{Fv} and split times for distances between 2 and 30 m) consistent with procedures previously reported (Buchheit et al., 2014; Cross et al., 2015; Morin & Seve, 2011).

Maximum velocity (vmax) was determined as the peak speed achieved during the 30 m sprint. The velocity-time curve [v(t)] for each sprint was fitted to an exponential function:

$$v(t) = vmax * (1 – e\text{-}t/\tau)$$

where t is the time and τ is the time constant. Instantaneous horizontal acceleration was calculated as the first derivative of the equation above and used to calculate F_h from Newton's second law of motion:

$$F_h(t) = [m * a(t)] + F_{air} (t)$$

where m is the body mass of the participant and F_{air} is the air friction during sprinting, which is influenced by the drag coefficient (Cd; 0.90), the density (ρ) and the frontal area of the participant (Af) (Arsac & Locatelli, 2002):

$$F_{air} = ½Cd * \rho * Af * vmax^2$$

$$\rho = 1.293 * (barometric\ pressure/760) * (273/(273 + ambient\ temperature))$$

*Af = (0.2025 * height0.725 * mass0.425) * 0.266*

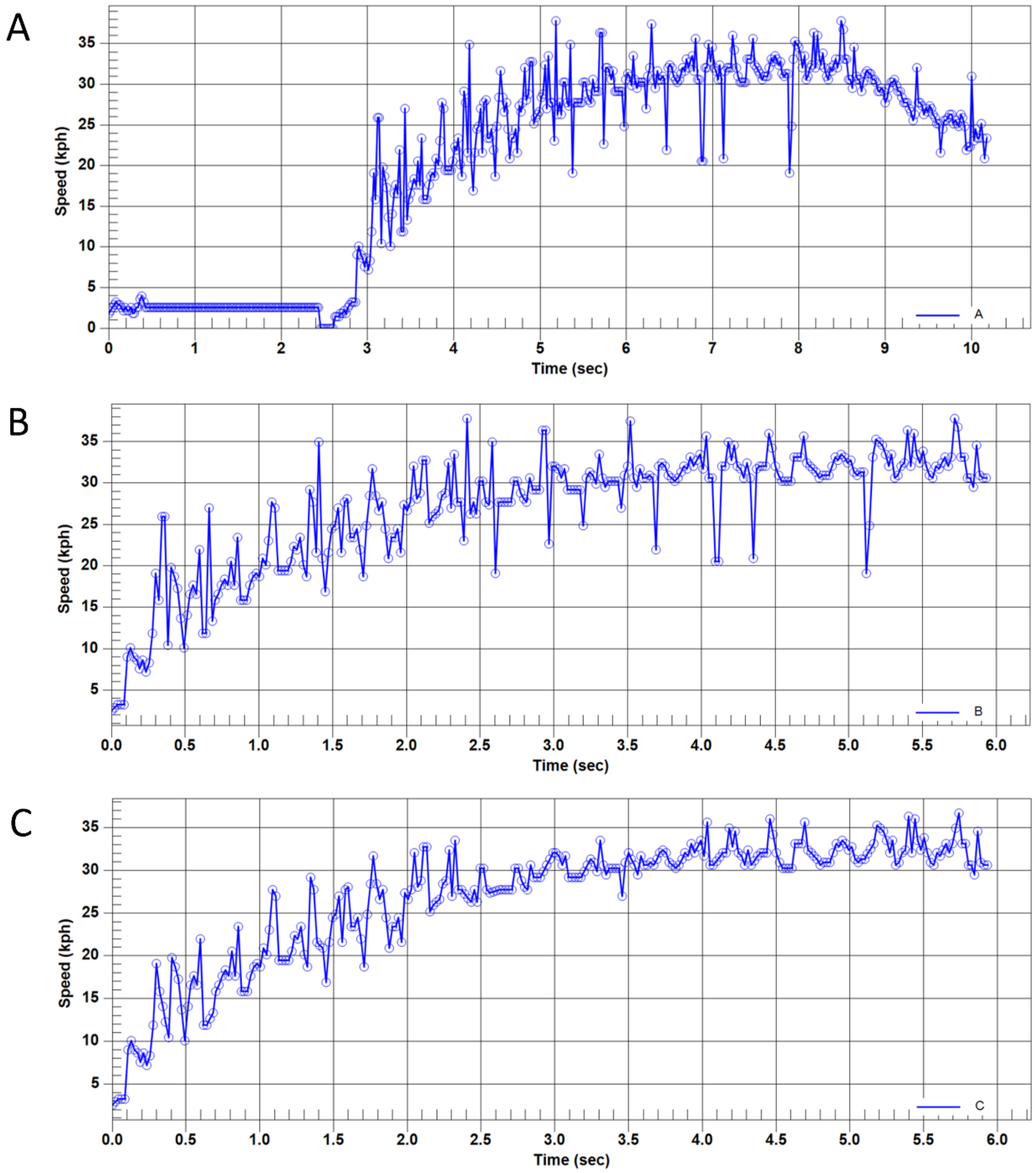

Figure 7. Illustration of the three key steps of the manual processing of the raw data files in the Stalker ATS System™ software: (A) raw radar data file; (B) all data recorded prior to the start and after the finish of sprint manually deleted and trial selected to be an 'acceleration run' (forcing the start of the velocity-time curve through the zero point); (C) manual removal of unexpected high and low data points on the velocity-time curve that were likely caused by segmental movements of the participants while sprinting.

F0 and V0 were determined as the y-axis and x-axis intercepts of the force-velocity curve and were used to calculate Pmax and S_{Fv}:

$Pmax = (0.5*F0) * (0.5*V0)$

$S_{Fv} = - F0 / V0$

Relative values for F0, Pmax and S_{Fv} were calculated by dividing by body mass, giving $F0_{rel}$, $Pmax_{rel}$ and S_{Fvrel} respectively.

Statistical Analyses

The mean and standard deviation (SD) was calculated for all radar-derived variables. The smallest worthwhile change, which is about 30% of the typical variation in an individual's performance from competition to competition, was also calculated as 0.2 multiplied by the between-participant SD for each variable (Hopkins, 2004).

The CV and ICC values for each outcome variable were calculated using a custom-made spreadsheet available online (Hopkins, 2015). For the intra-day analysis, the mean CV and ICC values from the three sprints were presented. For the inter-day analysis CV and ICC values were calculated for: Day 1 vs Day 2; Day 2 vs Day 3; Day 3 vs Day 4; and mean values across all four days of testing. These inter-day reliability values were calculated separately for comparisons of: (i) the first trial; (ii) the best trial (i.e. fastest 10 m split time); (iii) the median trial; (iv) the average of the first two trials; and, (v) the average of all three trials; from each testing session. The 90% confidence limits for all reliability results were also included. Repeated measures ANOVA with Bonferroni post-hoc contrasts were used to check for significant differences between trials or between testing sessions. The level of significance was set at $p \leq 0.05$.

The thresholds for interpreting ICC results were: 0.20-0.49 low, 0.50-0.74 moderate, 0.75-0.89 high, 0.90-0.98 very high and ≥ 0.99 extremely high (Hopkins, Marshall, Batterham, & Hanin, 2009). A CV of ≤ 10% was considered small (Bennell, Crossley, Wrigley, & Nitschke, 1999; Bradshaw, Hume, Calton, & Aisbett, 2010). The average reliability of each measure was interpreted as acceptable for an ICC ≥ 0.75 and a CV ≤ 10%, moderate when ICC < 0.75 or CV > 10%, and unacceptable/poor when ICC < 0.75 and CV > 10%.

Results

The mean, SD and smallest worthwhile change was calculated from the three sprints each participant completed on their first day of testing (Table 6). The mean typical error expressed as a CV was small (≤ 8.4%) for all variables for intra-day analysis (Table 6), however the 90% confidence limits included values greater than 10% for absolute and relative F0 and S_{Fv}. The intra-day CV is higher than the smallest worthwhile change for all radar-derived output variables. Mean ICC values were of only moderate strength for $F0_{rel}$ and $Pmax_{rel}$ and also for split times over the initial 10 m.

There were no significant differences observed between days for each of the variables when the best, median, average of two or average of three sprint trials were analysed. When the first sprint trial was analysed, there were significant differences between the week two and week four results for several variables (Pmax, $Pmax_{rel}$, and 5, 10, 20 m split times) ($F = 4.00$-4.75; $p \leq 0.05$).

There was no clear trend or indication of a learning effect when the reliability values were compared between days (i.e. Day 1 vs Day 2; Day 2 vs Day 3; Day 3 vs Day 4). All inter-day reliability values are therefore presented as an average across all four testing days (Table 7). Mean CV and ICC values tended to indicate higher variability when the first or best sprint trial was analysed, compared to the median or average of two or three trials. Analysis of the best trial resulted in good/acceptable reliability for all variables except $F0_{rel}$, S_{Fvrel} and 2 m and 5 m split times, which had moderate reliability due to ICC values between 0.60 and 0.73. When the average of two or three trials was analysed, the reliability was good/acceptable for all variables except S_{Fvrel} when using the average of the first two trials (ICC = 0.74) and the 2 m split time when using the average of three trials (ICC = 0.73). The inter-day CV was only lower than the smallest worthwhile change for $F0_{rel}$ (best, median and average of three trials), 20 m and 30 m splits (median, average of two and average of three trials), and the 20-30 m split (best, median and average of two and average of three trials).

Table 6. Means ± SD, smallest worthwhile change and intra-day reliability of radar-derived kinematic and kinetic variables from three 30 m sprints. CV and ICC values are presented as a mean together with 90% confidence limits. CV values ≥ 10% and ICC values < 0.75 highlighted in bold.

	Mean ± SD	**Smallest worthwhile change**	**CV (%)**	**ICC**
V0 (m/s)	**7.99 ± 0.53**	0.11	2.0 (1.5-3.1)	0.95 (0.86-0.98)
F0 (N)	**828 ± 181**	36	7.0 (5.3-**11.0**)	0.96 (0.89-0.99)
Pmax (W)	**1637 ± 288**	58	6.0 (4.6-9.4)	0.96 (0.88-0.99)
S_{Fv} (N/m/s)	**-105 ± 29**	6	8.4 (6.4-**13.2**)	0.96 (0.90-0.99)
$F0_{rel}$ (N/kg)	**8.64 ± 1.13**	0.23	6.9 (5.3-**10.9**)	**0.70** (**0.36**-0.89)
$Pmax_{rel}$ (W/kg)	**17.2 ± 2.6**	0.5	5.9 (4.5-9.3)	**0.74** (**0.42**-0.91)
S_{Fvrel} (N/m/s/kg)	**-1.11 ± 0.15**	0.03	8.1 (6.2-**12.8**)	0.79 (**0.52**-0.93)
2 m (s)	**0.74 ± 0.07**	0.01	5.5 (4.2-8.6)	**0.66** (**0.30**-0.88)
5 m (s)	**1.32 ± 0.09**	0.02	3.2 (2.5-5.0)	**0.71** (**0.38**-0.90)
10 m (s)	**2.11 ± 0.12**	0.02	2.1 (1.6-3.2)	**0.72** (**0.40**-0.90)
20 m (s)	**3.47 ± 0.18**	0.04	1.2 (0.9-1.9)	0.91 (0.77-0.97)
30 m (s)	**4.76 ± 0.25**	0.05	1.2 (0.9-1.8)	0.93 (0.82-0.98)
20-30 m (s)	**1.29 ± 0.08**	0.02	2.1 (1.6-3.3)	0.89 (0.73-0.97)
vmax (m/s)	**7.80 ± 0.49**	0.10	1.8 (1.4-2.9)	0.95 (0.86-0.98)

Note. SD = standard deviation; V0 = theoretical maximum velocity; F0 = theoretical maximum horizontal force; Pmax = maximum horizontal power output; S_{Fv} = slope of the force-velocity curve; $F0_{rel}$ = theoretical maximum horizontal force relative to BM; $Pmax_{rel}$ = maximum horizontal power output relative to BM; S_{Fvrel} = relative slope of the force-velocity curve; vmax = maximum velocity

Table 7. Inter-day reliability of radar-derived kinematic and kinetic variables from three 30 m sprints, completed on four separate days of testing. CV and ICC values are presented as a mean across the four testing sessions together with 90% confidence limits. CV values ≥ 10% and ICC values < 0.75 are highlighted in bold.

		First Trial	Best Trial	Median Trial	Avg. of 2 Trials	Avg. of 3 Trials
V0	CV (%)	3.4 (2.7-4.8)	2.1 (1.7-3.0)	2.3 (1.8-3.2)	2.3 (1.8-3.2)	2.2 (1.8-3.1)
	ICC	0.83 (**0.64**-0.94)	0.93 (0.83-0.98)	0.92 (0.81-0.97)	0.92 (0.82-0.97)	0.93 (0.83-0.98)
F0	CV (%)	7.3 (5.8-**10.5**)	7.3 (5.9-**10.5**)	5.6 (4.5-7.9)	4.9 (3.9-7.0)	5.7 (4.6-8.2)
	ICC	0.94 (0.86-0.98)	0.94 (0.87-0.98)	0.97 (0.92-0.99)	0.97 (0.94-0.99)	0.96 (0.91-0.99)
Pmax	CV (%)	5.8 (4.6-8.3)	6.4 (5.1-9.1)	4.3 (3.5-6.2)	3.8 (3.1-5.4)	4.7 (3.8-6.7)
	ICC	0.95 (0.88-0.98)	0.94 (0.86-0.98)	0.97 (0.92-0.99)	0.98 (0.94-0.99)	0.96 (0.91-0.99)
S_{Fv}	CV (%)	**10.0** (8.0-**14.4**)	8.8 (7.0-**12.6**)	7.3 (5.8-**10.4**)	6.7 (5.3-9.5)	7.3 (5.8-**10.4**)
	ICC	0.93 (0.83-0.98)	0.94 (0.87-0.98)	0.96 (0.91-0.99)	0.97 (0.92-0.99)	0.96 (0.91-0.99)
$F0_{rel}$	CV (%)	7.4 (5.9-**10.5**)	7.3 (5.8-**10.4**)	5.6 (4.5-8.0)	5.0 (4.0-7.1)	5.7 (4.6-8.2)
	ICC	**0.67** (**0.38**-0.88)	**0.71** (**0.45**-0.90)	0.76 (**0.52**-0.92)	0.82 (**0.63**-0.94)	0.78 (**0.55**-0.92)
$Pmax_{rel}$	CV (%)	5.9 (4.7-8.4)	2.1 (1.7-3.0)	2.3 (1.8-3.2)	3.9 (3.1-5.6)	2.2 (1.8-3.1)
	ICC	0.86 (**0.70**-0.95)	0.93 (0.83-0.98)	0.92 (0.81-0.97)	0.94 (0.85-0.98)	0.93 (0.83-0.98)
S_{Fvrel}	CV (%)	9.7 (7.7-**13.9**)	8.5 (6.8-**12.2**)	7.0 (5.6-**10.1**)	6.6 (5.2-9.4)	7.1 (5.7-**10.1**)
	ICC	**0.54** (**0.23**-0.82)	**0.71** (**0.45**-0.90)	**0.72** (**0.46**-0.90)	**0.74** (**0.49**-0.91)	0.76 (**0.52**-0.91)
2 m	CV (%)	6.4 (5.2-9.2)	5.4 (4.3-7.7)	5.0 (4.0-7.1)	4.0 (3.2-5.6)	4.4 (3.6-6.3)
	ICC	**0.49** (**0.17**-0.79)	**0.60** (**0.30**-0.85)	**0.66** (**0.37**-0.87)	0.75 (**0.51**-0.91)	**0.73** (**0.47**-0.90)
5 m	CV (%)	3.0 (2.4-4.3)	3.5 (2.8-4.9)	2.3 (1.9-3.3)	2.1 (1.7-2.9)	2.5 (2.0-3.5)
	ICC	0.80 (**0.58**-0.93)	**0.73** (**0.47**-0.90)	0.86 (**0.69**-0.95)	0.89 (0.75-0.96)	0.84 (**0.66**-0.95)

		First Trial	Best Trial	Median Trial	Avg. of 2 Trials	Avg. of 3 Trials
10 m	CV (%)	1.9 (1.6-2.8)	2.2 (1.8-3.1)	1.4 (1.2-2.0)	1.3 (1.0-1.8)	1.6 (1.3-2.3)
	ICC	0.86 (**0.70**-0.95)	0.81 (**0.59**-0.93)	0.90 (0.78-0.97)	0.93 (0.84-0.98)	0.89 (0.75-0.96)
20 m	CV (%)	1.4 (1.2-2.1)	1.3 (1.0-1.8)	1.1 (0.9-1.6)	0.9 (0.8-1.3)	1.1 (0.9-1.5)
	ICC	0.92 (0.81-0.97)	0.93 (0.84-0.98)	0.94 (0.87-0.98)	0.97 (0.92-0.99)	0.95 (0.88-0.98)
30 m	CV (%)	1.6 (1.2-2.2)	1.2 (1.0-1.7)	1.1 (0.9-1.5)	1.0 (0.8-1.4)	1.0 (0.8-1.4)
	ICC	0.92 (0.82-0.97)	0.95 (0.88-0.98)	0.96 (0.89-0.99)	0.97 (0.92-0.99)	0.96 (0.91-0.99)
20-30 m	CV (%)	2.7 (2.2-3.9)	1.7 (1.3-2.3)	1.5 (1.2-2.2)	1.7 (1.4-2.5)	1.4 (1.2-2.0)
	ICC	0.86 (**0.69**-0.95)	0.94 (0.85-0.98)	0.95 (0.87-0.98)	0.94 (0.85-0.98)	0.95 (0.89-0.99)
vmax	CV (%)	3.2 (2.5-4.5)	1.7 (1.3-2.3)	2.1 (1.7-2.9)	2.1 (1.7-3.0)	2.0 (1.6-2.9)
	ICC	0.83 (**0.65**-0.94)	0.94 (0.85-0.98)	0.92 (0.81-0.97)	0.92 (0.82-0.97)	0.93 (0.83-0.98)

Note. SD = standard deviation; V0 = theoretical maximum velocity; F0 = theoretical maximum horizontal force; Pmax = maximum horizontal power output; S_{Fv} = slope of the force-velocity curve; $F0_{rel}$ = theoretical maximum horizontal force relative to BM; $Pmax_{rel}$ = maximum horizontal power output relative to BM; S_{Fvrel} = relative slope of the force-velocity curve; vmax = maximum velocity

Discussion and Implications

This is the first report on the reliability of both radar-derived kinematic and kinetic variables together with the reliability of radar-derived split times for sprints between 2 m and 30 m. It was hypothesised that all tested variables would have acceptable reliability, but this can be rejected. Intra-day reliability was acceptable for most variables (i.e. V0, F0, Pmax, S_{Fv}, S_{Fvrel} and split times ≥ 20 m), but was only moderate for $F0_{rel}$, $Pmax_{rel}$ and split times ≤ 10 m. When the results were averaged over two or three trials and compared between days, the reliability was acceptable for all variables except S_{Fvrel} (when averaged over two trials) and 2 m time (when averaged over three trials) with only moderate reliability.

Higher levels of measurement variability in the present study were recorded for sprint distances over the initial 10 m as well as variables derived from F0, which also occurs at the start of a sprint acceleration (e.g. $F0_{rel}$, $Pmax_{rel}$ and S_{Fvrel}). Buchheit et al. (2014) also reported only moderate intra-day reliability for laser-derived values for $F0_{rel}$ (CV = 7.8%, ICC = 0.64), but reported acceptable intra-day reliability for V0, $Pmax_{rel}$ and S_{Fv} from a 40 m sprint (CV = 1.6-8.9%; ICC = 0.87-0.97). In the only between day comparison in the literature to date, Ferro et al. (2012) also identified only moderate relative reliability (ICC = 0.73) for maximum velocity achieved during the initial 10 m of a sprint, however mean velocity over the same 10 m section had slightly higher reliability (ICC = 0.76). It can be hypothesised that the reasons for the only moderate reliability of split times over the initial 10 m and certain variables that include a horizontal force component are due to increased variability in measured velocity during sprint starts. Subjectively, a consistent pattern of greater noise of measured velocity values was observed in the present study during the initial approximately two seconds of each sprint compared to the phases of later acceleration and maximum velocity (illustrated in Figure 7C). The increased variability during the first several steps of each sprint will impact not only on the calculation of sprint split times, but also on the calculation of instantaneous horizontal acceleration (i.e. the first derivative of instantaneous horizontal velocity), and therefore will also impact on the calculation of horizontal force.

Bezodis et al. (2012) compared video- and laser-derived values for velocity and concluded that the unacceptable level of error over the first 5 m with the laser results (limits of agreement = 0.41

± 0.18 m/s at 1 m and 0.13 ± 0.21 m/s at 5 m) was due mainly to the increasingly upright posture of the participants over this section of the sprint. The horizontal distance between the back of the participant and their COM was reported to change by approximately 0.25 m over the first 1 s of a sprint (Bezodis et al., 2012). A potential source of additional measurement error is introduced when manual post-processing of raw data files is required to set the start point of each sprint and to remove unexpectedly high and low data points (particularly at the beginning of each sprint), as was required in the current study. Utilising a 'rolling' start, whereby all sprint trials begin from 1 m/s rather than from 0 m/s, may help to reduce both of these sources of error and should be trialled in the future. It should be noted that while this method may improve reliability, important information from the crucial first steps of acceleration would be lost.

In practice the best sprint trial is often monitored for changes in speed performance and researchers concluded that there was little difference when analysing the best or average sprint performance over time when using dual beam electronic timing gates (Al Haddad, Simpson, & Buchheit, 2015). It should be noted however that after four months of training the authors identified 33% more players showing a likely increase in 10 m performance and 50% less players showing a likely decrease in 10 m performance when analysing the average of two compared to the best sprint trial (Al Haddad et al., 2015). The findings in the current study indicate that, depending on the outcome measure of choice, improved measurement reliability may be achieved with a radar device by tracking the average of two or three sprints rather than the best repetition of three sprints. Acceptable reliability was achieved for sprints of 5 m or greater when the first trial, median trial or average of two to three trials was analysed, and for sprints of 10 m or greater when the best trial of three was analysed. Taking the average of the first two trials was the only method to result in acceptable reliability for 2 m split times. For athletes interested in acceleration performance over distances as short as 2 and 5 m (e.g. court-based and many field-based team sport athletes), tracking changes in average sprint performance over multiple repetitions should be preferred over one-off best sprint performances. Analysis of average sprint performance also resulted in good reliability of measurements of $F0_{rel}$, whereas only moderate reliability was achieved when analysing the first or best trial.

Samozino et al. (2012) suggested that training can be individualised for relatively force-dominant and relatively velocity-dominant athletes based on S_{Fvrel} results, however practitioners should be aware of the moderate inter-day reliability of S_{Fvrel}. While the best, median or average trial all resulted in acceptable inter-day reliability for S_{Fv}, S_{Fvrel} had only moderate inter-day reliability unless an average of three trials was used.

Limitations of the current study include that the participants were young team sport athletes with minimal structured speed training experience. It may be hypothesised that the contribution of athlete biological variation may be less for more highly trained athletes or sprinters. The reliability statistics reported relate specifically to the testing protocols and data analysis procedures used in the current study. Alternate methods of post-processing of the data, including modifications to the custom-made LabView program, may result in changes in the practical reliability of the radar profiling. Finally, in order to make firm conclusions about small changes in performance, it is ideal if the typical error (or 'noise') associated with a test is less than the smallest worthwhile change (Hopkins, 2004). However, in the current study, intra-day typical error (CV) was greater than the smallest worthwhile change for all variables. Inter-day typical error (CV) was lower than the smallest worthwhile change only for split times of 20 m and greater and for $Pmax_{rel}$. This has sample size and data processing implications for researchers and practitioners using radar to detect small changes in performance.

In conclusion, the majority of radar-derived kinematic and kinetic variables have acceptable reliability (i.e. ICC $\geq$ 0.75 and CV $\leq$ 10%) for measuring short sprint acceleration performance, however split times over the initial 10 m and some variables that incorporate $F0_{rel}$ have only moderate reliability. Decisions on whether to analyse best or average sprint performance will impact on measurement reliability and should be made based on the outcome variables of interest. Future research should investigate the strength of association between the radar-derived values that summarise the mechanical capabilities of the body (i.e. V0, $F0_{rel}$, $Pmax_{rel}$) and short sprint acceleration performance to facilitate an improved understanding of the practical utility of these variables.

Conclusions

All radar-derived kinematic and kinetic descriptors of short sprint performance have at least moderate intra-day and inter-day reliability. Radar technology can therefore be a useful tool for monitoring changes in the mechanical capabilities of the body (including horizontal force and power production) and sprint performance over distances as short as 2 m. Practitioners should average sprint test results over at least two trials to reduce measurement variability, particularly for outcome variables with a horizontal force component and for sprint distances of less than 10 m from the start.

CHAPTER 4

RELIABILITY OF SHORT SPRINT-RUNNING ACCELERATIONS ASSESSED ON A NON-MOTORISED TREADMILL

This paper comprises the following paper submitted to *Sports Biomechanics*:

Simperingham, K. D., Cronin, J. B., Ross, A., Compton, A. & Brown, S. (2019). Reliability of short sprint-running accelerations assessed on a non-motorised treadmill. *Sports Biomechanics, [In review]*.

Prelude

The main finding in the previous chapter was that most radar-derived 30 m sprint performance variables had acceptable reliability, however comparing the average of two trials between days improved reliability, which was especially important for variables that were calculated during the initial 10 m of a sprint (e.g. 5 m split time, F0, Pmax and S_{Fv}). In addition to the findings about radar and laser devices, the systematic literature review in Chapter 2 also summarised several important procedures and technical points that were required to ensure reliable results from sprint analyses using NMT and torque treadmill devices (e.g. a sampling rate ≥ 200 Hz and calculating kinetic variables during the period of foot contact only). A need for further research was highlighted specifically around assessing the reliability of kinematic and kinetic variables during a 10-step section of the acceleration phase. The aim of the following chapter was to largely replicate the reliability analysis from Chapter 3, but to use NMT technology instead of a radar device. Short (30 m) treadmill sprints were split into the start phase (steps 1-2), the acceleration phase (steps 3-12) and the maximum velocity phase (steps 13-22) for analysis. Consistent with the previous chapter, average reliability was interpreted as acceptable for an ICC ≥ 0.75 and a CV ≤ 10%.

Introduction

The reliable assessment of short-distance (≤ 30 m) sprint performance is crucial for informing team sport strength and conditioning coaches, and sport scientists to guide subsequent training programme design (Simperingham, Cronin, & Ross, 2016). While determining split times to cover set distances (e.g. 5 to 40 m sprints) measured with photoelectric cells is a reliable option (Cronin & Templeton, 2008; Grant M. Duthie et al., 2006), it is very limited in providing any useful information regarding the factors contributing to the sprint performance (Mendez-Villanueva & Buchheit, 2013). An NMT is an advanced diagnostic tool that enables an instantaneous and step-by-step analysis of a sprint effort across a range of kinetic and kinematic variables, including split times.

Key NMT-derived variables include: vertical GRF (F_v; measured directly with load cells under the treadmill belt surface), horizontal GRF (F_h; typically calculated indirectly using Newton's Third Law of Motion by measuring the horizontal force through a load cell positioned directly behind the sprinter's centre-of-mass and connected by a rigid tether to a waist belt), horizontal power (the product of sprint-velocity and F_h), contact time (CT), flight time (FT), step length (SL) and step frequency (SF). Stepwise calculation of these output variables also enables the analysis of limb symmetry (Brown, Brughelli, & Cross, 2016).

Short-distance sprint split times and velocities were reported to be up to 67% slower on a NMT compared to over-ground and only 9 to 64% of the variance in over-ground measurements was explained by the NMT results (Highton et al., 2012; Hopker et al., 2009). Furthermore, it was previously concluded that unacceptable reliability (CV > 10% and/or ICC < 0.75) meant that NMT analysis was impractical for detecting very small changes in sprint performance (Sirotic & Coutts, 2008; Tong et al., 2001). However, a recent systematic review of the relevant literature summarised five key techniques that are important to improve reliability of short-distance sprints on a NMT: sufficient familiarisation; a sampling rate of at least 200 Hz; a "blocked" start position (where movement of the treadmill belt prior to the sprint start is eliminated by the experimenter manually placing a foot on the belt surface); averaging results over multiple sprints; and stepwise analysis (i.e. analysing the period of each ground contact rather than averaging over an arbitrary time period) (Simperingham, Cronin, & Ross, 2016). By implementing these guidelines, NMT analysis can provide a readily accessible, reliable option for quantifying potentially useful details of sprint performance in the absence of long stretches of expensive in-ground force plates.

Hopker et al. (2009) suggested that at least three NMT familiarisation sessions may be required to ensure acceptable reliability, however this conclusion was based on a very low volume of treadmill sprinting during each session. Familiarisation sessions can be time consuming and impractical. The aim of this study was to determine if acceptable inter-day reliability of NMT-derived kinematic and kinetic measurements of short-distance (≤ 30 m) sprint-running acceleration performance could be achieved without the need for a separate familiarisation session by utilising an extended NMT warm-up protocol prior to each testing session. Intra-day reliability of all NMT-derived variables was also assessed after implementing all techniques that were considered important for achieving acceptable reliability of outputs (Simperingham, Cronin, & Ross, 2016). The study aims involve assessing the applied/practical reliability of the testing, which includes both potential variability in the methods used (instrument and analytical), along with athlete biological variations. It was hypothesised that all NMT-derived measures would have acceptable intra-day and inter-day reliability (ICC ≥ 0.75 and a CV ≤ 10%) without the need for a separate familiarisation session.

Methods

This study involved an assessment of the variability of 30 m sprint performance measured with a NMT device across three sprints during one session (intra-day analysis) and across four identical testing sessions (inter-day analysis). To control the testing conditions as much as possible, all testing sessions for each participant were performed on the same day of the week, at approximately the same time of the day and on the same treadmill in a laboratory setting. Testing sessions were repeated at weekly intervals unless illness or minor injury required that an additional week of rest was required. Participants were requested to avoid 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. Absolute reliability of the kinematic and kinetic outcome variables was examined by calculating the typical error of measurement expressed as a CV and relative reliability was examined with the ICC (Hopkins, 2000, 2015).

Participants

Fourteen amateur club or provincial age-group representative male rugby union players volunteered to participate in this study (age 19.0 ± 0.4 years; body mass 95.4 ± 19.5 kg; height 180.2 ± 6.6 cm). All participants completed at least one testing session (intra-day analysis), while eight participants completed all four testing sessions for the inter-day analysis (age 18.8 ± 0.4 years; body mass 100.6 ± 21.6 kg; height 177.4 ± 5.1 cm). All discomforts and risks associated with the study were explained prior to participants providing their written informed consent to participate. The study had full ethical approval from the Institutional Ethics Committee.

Procedures

Participants reported to the laboratory in athletic clothing and wearing running shoes. Height and body mass were recorded without shoes. A 15-minute standardised warm-up was completed on an indoor track (including jogging, sprint drills, dynamic stretching and build-up sprints of increasing intensity up to maximal effort). A further treadmill-specific warm-up followed on the NMT (Woodway Force 3.0, Woodway USA Inc., Waukesha, WI, USA) involving: a 30 s constant pace jog, finishing with one acceleration run up to approximately 75% effort; two 6 s sprints at 75-80% effort from a stationary start; two 3 s sprints at greater than 90% effort from a stationary start. There was then a period of five minutes of passive rest prior to each of the three maximal effort 30 m sprint trials.

Participants started every sprint from a stationary split stance position. A “blocked start” was used, enabling participants to maintain a natural standing split stance position with the body leaning forward, but without the treadmill belt moving prior to the sprint start. F_v was collected from four load cells underneath the treadmill belt. F_h was estimated from a horizontal load cell attached to a vertical strut directly behind the treadmill. Participants wore a waist belt attached by a rigid tether to the horizontal load cell. The height of the load cell was adjusted to roughly the sprinter's centre-of-mass height to ensure that the tether remained parallel to the treadmill surface during each sprint. Calibration and data collection methods were consistent with earlier studies and enabled the stepwise calculation of mean F_v, peak F_v, peak F_h and peak horizontal power output (PP), all expressed relative to body mass (Brown, Brughelli, & Cross, 2016; Brown et al., 2017; Cross et al., 2014). Maximum velocity was measured from the speed of the treadmill belt. Three distinct sprinting phases were analysed: (i) the start phase (steps 1-2); (ii) the acceleration phase (steps 3-12); and, (iii) the maximum velocity phase (steps 13-22) (Brown, Brughelli, & Cross, 2016; Simperingham & Cronin, 2014). CT, FT, SL and SF were averaged over the ten steps of the acceleration and maximum velocity phases. Data was collected through the treadmill system interface (XPv7 PCB, Fitness Technology, Adelaide, AUS) (200 Hz) and a custom-built LabVIEW (Version 13.0, National Instruments, Texas, USA) software program was used for post-processing.

Statistical Analyses

The mean and SD was calculated for all treadmill-derived variables. The smallest worthwhile change, which is about 30% of the typical variation in an individual's performance from competition to competition, was also calculated as 0.2 multiplied by the between-participant SD for each variable (Hopkins, 2004).

The CV and ICC values for each outcome variable were calculated using a custom-made spreadsheet available online (Hopkins, 2015). For the intra-day analysis the mean CV and ICC values from the three sprints were presented. For the inter-day analysis CV and ICC values were calculated for: Day 1 vs Day 2; Day 2 vs Day 3; Day 3 vs Day 4; and mean values across all four days of testing. These inter-day reliability values were calculated separately for comparisons of: (i) the first trial; (ii) the best trial (i.e. fastest 10 m split time); (iii) the average of the first two trials; and, (iv) the average of all three trials; from each testing session. The 90% confidence limits for all reliability results were also included. Repeated measures ANOVA with Bonferroni post-hoc contrasts were used to check for significant differences between trials or between testing sessions. The level of significance was set at $p \leq 0.05$.

The thresholds for interpreting ICC results were: 0.20-0.49 low, 0.50-0.74 moderate, 0.75-0.89 high, 0.90-0.98 very high and ≥ 0.99 extremely high (Hopkins et al., 2009). A CV of ≤ 10% was considered small (Bennell et al., 1999; Bradshaw et al., 2010). The average reliability of each measure was interpreted as acceptable for an ICC ≥ 0.75 and a CV ≤ 10%, moderate when ICC < 0.75 or CV > 10%, and unacceptable/poor when ICC < 0.75 and CV > 10% (Simperingham, Cronin, Pearson, & Ross, 2019).

Results

Intra-day Reliability

The mean, SD and smallest worthwhile change was calculated from the three sprints each participant completed on their first day of testing. The average intra-day reliability was summarised as acceptable (ICC ≥ 0.75 and a CV ≤ 10%), moderate (ICC < 0.75 or CV > 10%) or unacceptable (ICC < 0.75 and CV > 10%) for split times and maximum velocity (Table 8) and for kinetic variables and CT, FT, SL and SF (Table 9).

Intra-day reliability was acceptable for maximum velocity and all sprint times except the 5 m split time, which had only moderate reliability (ICC = 0.71) (Table 8).

Start phase: average intra-day reliability of all kinetic variables was unacceptable during the start phase, except for mean F_v (moderate reliability).

Acceleration phase: average intra-day reliability was acceptable for all kinetic variables except mean F_v (moderate reliability), and was also acceptable for CT, SL and SF, but unacceptable for FT.

Maximum velocity phase: average intra-day reliability was acceptable for all variables except CT (moderate reliability).

When intra-day reliability was deemed only moderate, it was due to relatively low relative reliability values (ICC < 0.75). It should be noted that several variables with acceptable reliability actually had 90% confidence limits that included ICC values less than 0.75 (acceleration phase peak F_v, CT, SL, SF; maximum velocity phase peak and mean F_v, CT, SL, SF). The only significant differences between trials were in the maximum velocity phase where peak F_h was significantly higher in the third trial compared to the first trial ($p = 0.01$, $F = 5.76$) and mean F_v was significantly lower in the third trial compared to the second trial ($p = 0.03$, $F = 3.72$).

Inter-day Reliability

After four separate days of NMT sprint testing, there was no clear indication of a learning effect when the reliability values were compared between days (i.e. Day 1 vs Day 2; Day 2 vs Day 3; Day 3 vs Day 4). All inter-day reliability values are therefore presented as an average across all four testing days (Table 10). Significant inter-day differences were observed for acceleration phase PP (Day 4 higher than Day 1 for average of two and average of three trials only), maximum velocity phase mean F_v (Day 2 and 4 higher than Day 1 under all analysis conditions, while Day 3 was also higher than Day 1 when the best trial only was analysed) and maximum velocity phase CT (Day 3 longer than Day 1 for average of three trials only) ($F = 3.25 - 11.95$, $p \leq 0.05$). Sprint times of 20 m and less were also significantly faster on Day 4 compared to Day 1 (although not over 5 and 10 m when the best trial only was analysed) ($F= 4.02 - 6.96$, $p \leq 0.05$).

Mean CV and ICC values tended to indicate higher variability when the first or best sprint trial was analysed, while inter-day reliability was moderate or acceptable for all variables when the average of two trials was used. Acceleration phase FT was the only variable with unacceptable inter-day reliability when the average of all three trials were used. When the first trial or best trial was used several variables had unacceptable reliability: start phase peak F_v and PP; acceleration phase FT; and, maximum velocity phase mean F_v (best trial only). The inter-day CV was only lower than the smallest worthwhile change for SL, SF, acceleration phase PP (average of two and average of three trials only), acceleration phase peak F_h (best trial, average of two and average of three trials only) and maximum velocity phase peak F_h (average of two and average of three trials only).

Table 8. Means ± SD, smallest worthwhile change and intra-day reliability of NMT-derived short (30 m) sprint split times and maximum velocity. CV and ICC values are presented as a mean from three sprints together with 90% confidence limits. Reliability was summarised as acceptable (ICC ≥ 0.75 and a CV ≤ 10%), moderate (ICC < 0.75 or CV > 10%) or unacceptable (ICC < 0.75 and CV > 10%).

	Mean ± SD	**Smallest Worthwhile Change**	**CV (%)**	**ICC**	**Reliability**
5 m (s)	1.92 ± 0.08	0.02	2.6 (2.0-4.0)	0.71 (0.38-0.90)	Moderate
10 m (s)	2.86 ± 0.11	0.02	2.0 (1.5-3.1)	0.76 (0.46-0.92)	Acceptable
20 m (s)	4.66 ± 0.16	0.03	1.2 (1.0-1.9)	0.87 (0.67-0.96)	Acceptable
30 m (s)	6.49 ± 0.24	0.05	1.0 (0.8-1.6)	0.90 (0.75-0.97)	Acceptable
20-30 m (s)	1.83 ± 0.10	0.02	1.3 (1.0-2.0)	0.85 (0.64-0.95)	Acceptable
vmax (m/s)	5.68 ± 0.21	0.04	1.2 (0.9-1.8)	0.87 (0.67-0.96)	Acceptable

Note. SD = standard deviation; CV = coefficient of variation; ICC = intraclass correlation coefficient; vmax = maximum velocity

Table 9. Means ± SD, smallest worthwhile change and intra-day reliability of NMT-derived kinetic and kinematic variables from three 30 m sprints. CV and ICC values are presented as a mean from three sprints together with 90% confidence limits. Reliability was summarised as acceptable (ICC ≥ 0.75 and a CV ≤ 10%), moderate (ICC < 0.75 or CV > 10%) or unacceptable (ICC < 0.75 and CV > 10%).

	Phase	**Mean ± SD**	**Smallest Worthwhile Change**	**CV (%)**	**ICC**	**Reliability**
Peak F_v (N/kg)	Start	15.8 ± 2.2	0.5	12.5 (9.5-19.9)	0.59 (0.20-0.85)	Unacceptable
	Acceleration	20.8 ± 1.4	0.3	2.9 (2.2-4.6)	0.79 (0.52-0.93)	Acceptable
	Max. velocity	22.6 ± 1.4	0.3	2.0 (1.5-3.0)	0.88 (0.69-0.96)	Acceptable
Mean F_v (N/kg)	Start	10.1 ± 0.5	0.1	3.9 (3.0-6.2)	0.70 (0.36-0.89)	Moderate
	Acceleration	9.5 ± 0.2	0.03	1.1 (0.8-1.6)	0.63 (0.25-0.86)	Moderate
	Max. velocity	9.8 ± 0.1	0.03	0.4 (0.3-0.5)	0.86 (0.67-0.96)	Acceptable
Peak F_h (N/kg)	Start	7.3 ± 2.3	0.5	29.0 (21.7-48.3)	0.71 (0.38-0.90)	Unacceptable
	Acceleration	4.0 ± 0.8	0.2	5.3 (4.0-8.3)	0.97 (0.92-0.99)	Acceptable
	Max. velocity	3.4 ± 0.6	0.1	4.1 (3.1-6.4)	0.97 (0.93-0.99)	Acceptable
PP (W/kg)	Start	16.0 ± 6.3	1.3	82.1 (58.7-152.6)	0.54 (0.13-0.82)	Unacceptable
	Acceleration	19.6 ± 3.9	0.8	3.7 (2.8-5.8)	0.98 (0.95-0.99)	Acceptable
	Max. velocity	19.0 ± 3.4	0.7	5.3 (4.1-8.3)	0.95 (0.86-0.98)	Acceptable
CT (s)	Acceleration	0.188 ± 0.016	0.003	3.5 (2.7-5.5)	0.87 (0.68-0.96)	Acceptable
	Max. velocity	0.173 ± 0.013	0.003	3.2 (2.5-5.0)	0.66 (0.30-0.88)	Moderate
FT (s)	Acceleration	0.047 ± 0.008	0.002	20.5 (15.4-33.3)	0.70 (0.36-0.90)	Unacceptable
	Max. velocity	0.060 ± 0.010	0.002	6.4 (4.9-10.0)	0.90 (0.75-0.97)	Acceptable
SL (m)	Acceleration	1.25 ± 0.07	0.01	2.8 (2.2-4.4)	0.81 (0.55-0.94)	Acceptable
	Max. velocity	1.32 ± 0.09	0.02	1.5 (1.1-2.3)	0.89 (0.72-0.96)	Acceptable
SF (Hz)	Acceleration	4.28 ± 0.23	0.05	2.8 (2.2-4.4)	0.84 (0.60-0.95)	Acceptable
	Max. velocity	4.31 ± 0.23	0.05	1.2 (0.9-1.9)	0.94 (0.83-0.98)	Acceptable

Note. SD = standard deviation; CV = coefficient of variation; ICC = intraclass correlation coefficient; F_v = vertical ground reaction force; F_h = horizontal ground reaction force; PP = peak horizontal power output; CT = contact time; FT = flight time; SL = step length; SF = step frequency

Table 10. Inter-day reliability of NMT-derived kinematic and kinetic variables from three 30 m sprints, completed on four separate days of testing. CV and ICC values are presented as a mean across the four testing sessions together with 90% confidence limits. Reliability was summarised as acceptable (ICC ≥ 0.75 and a CV ≤ 10%), moderate (ICC < 0.75 or CV > 10%) or unacceptable (ICC < 0.75 and CV > 10%).

	Phase		First Trial	Best Trial	Avg. of 2 Trials	Avg. of 3 Trials
5 m		CV (%)	2.9 (2.3-4.2)	2.9 (2.3-4.2)	2.7 (2.1-3.9)	2.5 (2.0-3.7)
		ICC	0.74 (0.46-0.91)	0.70 (0.41-0.90)	0.76 (0.50-0.92)	0.77 (0.51-0.92)
			Moderate	Moderate	Acceptable	Acceptable
10 m		CV (%)	2.5 (2.0-3.6)	2.1 (1.7-3.1)	2.1 (1.6-3.0)	2.0 (1.6-2.9)
		ICC	0.76 (0.50-0.92)	0.80 (0.57-0.94)	0.82 (0.61-0.94)	0.82 (0.61-0.94)
			Acceptable	Acceptable	Acceptable	Acceptable
20 m		CV (%)	1.7 (1.3-2.4)	1.4 (1.1-2.0)	1.5 (1.2-2.2)	1.5 (1.1-2.1)
		ICC	0.86 (0.68-0.96)	0.90 (0.75-0.97)	0.88 (0.71-0.96)	0.89 (0.73-0.97)
			Acceptable	Acceptable	Acceptable	Acceptable
30 m		CV (%)	1.5 (1.2-2.1)	1.1 (0.9-1.6)	1.4 (1.1-2.0)	1.3 (1.0-1.8)
		ICC	0.89 (0.74-0.97)	0.94 (0.84-0.98)	0.90 (0.75-0.97)	0.92 (0.80-0.97)
			Acceptable	Acceptable	Acceptable	Acceptable
20-30 m		CV (%)	2.4 (1.9-3.5)	2.2 (1.7-3.2)	1.7 (1.3-2.4)	1.6 (1.3-2.4)
		ICC	0.73 (0.45-0.91)	0.81 (0.59-0.94)	0.87 (0.69-0.96)	0.88 (0.73-0.97)
			Moderate	Acceptable	Acceptable	Acceptable
vmax		CV (%)	1.9 (1.5-2.7)	1.1 (0.8-1.5)	1.5 (1.1-2.1)	1.4 (1.1-2.0)
		ICC	0.84 (0.63-0.95)	0.95 (0.88-0.99)	0.89 (0.75-0.97)	0.92 (0.80-0.97)
			Acceptable	Acceptable	Acceptable	Acceptable
Peak F_v	Start	CV (%)	12.1 (9.5-17.8)	12.4 (9.6-18.2)	6.6 (5.2-9.6)	6.5 (5.1-9.5)
		ICC	0.57 (0.24-0.84)	0.58 (0.25-0.85)	0.84 (0.64-0.95)	0.87 (0.69-0.96)
			Unacceptable	Unacceptable	Acceptable	Acceptable
	Acceleration	CV (%)	4.1(3.3-6.0)	3.6 (2.8-5.2)	2.8 (2.2-4.1)	2.8 (2.2-4.0)
		ICC	0.74 (0.46-0.91)	0.73 (0.45-0.91)	0.82 (0.61-0.94)	0.82 (0.60-0.94)
			Moderate	Moderate	Acceptable	Acceptable
	Max. velocity	CV (%)	3.5 (2.8-5.1)	2.6 (2.1-3.8)	2.7 (2.1-3.9)	2.4 (1.9-3.4)
		ICC	0.71 (0.42-0.90)	0.80 (0.57-0.94)	0.79 (0.56-0.93)	0.83 (0.63-0.95)
			Moderate	Acceptable	Acceptable	Acceptable

Mean F_v	Start	CV (%)	4.2 (3.3-6.1)	4.4 (3.4-6.3)	2.5 (2.0-3.6)	3.0 (2.4-4.3)
		ICC	0.31(-0.01-0.70)	0.27(-0.05-0.67)	0.51 (0.17-0.81)	0.45 (0.11-0.78)
			Moderate	Moderate	Moderate	Moderate
	Acceleration	CV (%)	1.7 (1.3-2.5)	1.2 (0.9-1.7)	1.2 (0.9-1.7)	1.0 (0.8-1.4)
		ICC	0.32(-0.01-0.71)	0.68 (0.38-0.89)	0.47 (0.13-0.79)	0.63 (0.31-0.87)
			Moderate	Moderate	Moderate	Moderate
	Max. velocity	CV (%)	0.5 (0.4-0.7)	12.4 (9.6-18.2)	0.5 (0.4-0.8)	6.5 (5.1-9.5)
		ICC	0.70 (0.40-0.90)	0.58 (0.25-0.85)	0.64 (0.32-0.87)	0.87 (0.69-0.96)
			Moderate	Unacceptable	Moderate	Acceptable
Peak F_h	Start	CV (%)	16.0 (12.4-23.7)	16.2 (12.6-24.1)	12.4 (9.7-18.3)	10.3 (8.0-15.1)
		ICC	0.87 (0.69-0.96)	0.89 (0.74-0.97)	0.92 (0.81-0.98)	0.94 (0.86-0.98)
			Moderate	Moderate	Moderate	Moderate
	Acceleration	CV (%)	5.2 (4.1-7.5)	3.6 (2.9-5.3)	4.1 (3.2-5.9)	3.5 (2.8-5.1)
		ICC	0.97 (0.93-0.99)	0.99 (0.96-1.00)	0.98 (0.95-0.99)	0.99 (0.97-1.00)
			Acceptable	Acceptable	Acceptable	Acceptable
	Max. velocity	CV (%)	5.2 (4.1-7.5)	4.9 (3.8-7.0)	3.5 (2.7-5.0)	3.4 (2.6-4.8)
		ICC	0.95 (0.88-0.99)	0.96 (0.89-0.99)	0.98 (0.94-0.99)	0.98 (0.95-0.99)
			Acceptable	Acceptable	Acceptable	Acceptable
PP	Start	CV (%)	45.3 (34.3-71.0)	36.1 (27.5-55.6)	20.6 (15.9-30.8)	19.4 (15.0-29.0)
		ICC	0.16(-0.13-0.58)	0.55 (0.21-0.83)	0.80 (0.57-0.94)	0.81 (0.59-0.94)
			Unacceptable	Unacceptable	Moderate	Moderate
	Acceleration	CV (%)	4.6 (3.6-6.7)	4.1 (3.2-5.9)	3.8 (3.0-5.6)	3.4 (2.7-5.0)
		ICC	0.98 (0.94-0.99)	0.98 (0.94-0.99)	0.98 (0.95-0.99)	0.98 (0.96-1.00)
			Acceptable	Acceptable	Acceptable	Acceptable
	Max. velocity	CV (%)	5.3 (4.2-7.7)	16.2 (12.6-24.1)	4.0 (3.1-5.7)	10.3 (8.0-15.1)
		ICC	0.94 (0.85-0.98)	0.89 (0.74-0.97)	0.97 (0.91-0.99)	0.94 (0.86-0.98)
			Acceptable	Moderate	Acceptable	Moderate
CT	Acceleration	CV (%)	6.3 (5.0-9.2)	7.2 (5.6-10.5)	4.1 (3.3-6.0)	3.7 (2.9-5.4)
		ICC	0.72 (0.43-0.91)	0.51 (0.17-0.82)	0.85 (0.65-0.95)	0.87 (0.70-0.96)
			Moderate	Moderate	Acceptable	Acceptable
	Max. velocity	CV (%)	3.1 (2.4-4.4)	4.0 (3.2-5.8)	3.1 (2.4-4.5)	2.9 (2.3-4.2)
		ICC	0.75 (0.48-0.92)	0.52 (0.19-0.82)	0.60 (0.28-0.86)	0.64 (0.33-0.87)
			Acceptable	Moderate	Moderate	Moderate
FT	Acceleration	CV (%)	14.0 (10.9-20.7)	48.3 (36.4-75.9)	9.9 (7.8-14.5)	13.8 (10.7-20.3)

		ICC	0.67 (0.36-0.89)	0.13(-0.15-0.56)	0.78 (0.54-0.93)	0.65 (0.34-0.88)
			Unacceptable	Unacceptable	Acceptable	Unacceptable
	Max. velocity	CV (%)	6.8 (5.3-9.9)	9.5 (7.4-13.9)	6.1 (4.8-8.9)	5.7 (4.5-8.3)
		ICC	0.88 (0.73-0.96)	0.75 (0.49-0.92)	0.87 (0.71-0.96)	0.88 (0.71-0.96)
			Acceptable	Acceptable	Acceptable	Acceptable
SL	Acceleration	CV (%)	5.1 (3.9-8.6)	4.5 (3.4-7.6)	3.5 (2.7-6.0)	3.1 (2.4-5.2)
		ICC	0.60 (0.18-0.87)	0.26 (0.10-0.70)	0.66 (0.26-0.89)	0.66 (0.27-0.89)
			Moderate	Moderate	Moderate	Moderate
	Max. velocity	CV (%)	2.1 (1.6-3.6)	2.1 (1.6-3.5)	2.2 (1.7-3.7)	2.0 (1.5-3.3)
		ICC	0.84 (0.59-0.95)	0.78 (0.46-0.93)	0.80 (0.51-0.94)	0.83 (0.56-0.95)
			Acceptable	Acceptable	Acceptable	Acceptable
SF	Acceleration	CV (%)	4.0 (3.1-6.7)	4.1 (3.2-7.0)	2.7 (2.1-4.5)	1.8 (1.4-2.9)
		ICC	0.78 (0.46-0.93)	0.46 (0.01-0.81)	0.86 (0.64-0.96)	0.89 (0.71-0.97)
			Acceptable	Moderate	Acceptable	Acceptable
	Max. velocity	CV (%)	1.4 (1.1-2.4)	2.4 (1.8-4.0)	1.7 (1.3-2.8)	1.8 (1.4-2.9)
		ICC	0.94 (0.84-0.98)	0.78 (0.47-0.93)	0.91 (0.74-0.97)	0.89 (0.71-0.97)
			Acceptable	Acceptable	Acceptable	Acceptable

Note. CV = coefficient of variation; ICC = intraclass correlation coefficient; vmax = maximum velocity; F_v = vertical ground reaction force; F_h = horizontal ground reaction force; PP = peak power output; CT = contact time; FT = flight time; SL = step length; SF = step frequency

Discussion and Implications

The aim of the study was to provide an in-depth analysis of the applied/practical reliability of NMT testing, which included quantifying the variability in the methods used (instrument and analytical), in tandem with athlete biological variations. The main findings were: 1) one familiarisation session was required to achieve acceptable reliability; 2) intra-day reliability was moderate to acceptable for almost all kinematic and kinetic variables during the acceleration and maximum velocity phases, but unacceptable during the start phase; and, 3) analysis of the first or best sprint trial tended to result in higher inter- day variability compared to the analysis of the average of two or three sprint trials.

It was hypothesised that a separate familiarisation session would be unnecessary if an extended treadmill-specific warm-up (including 30 s of treadmill jogging and four submaximal sprints from a stationary start) was combined with the implementation of all other key techniques that are known to be important for ensuring reliability of short-distance sprints on a NMT (i.e. a sampling rate ≥ 200 Hz; a "blocked" start position; averaging results over multiple sprints; and stepwise analysis) (Simperingham, Cronin, & Ross, 2016). This hypothesis should be rejected, but one familiarisation session (including five submaximal and three maximal sprints) appears sufficient to ensure no further learning effect would impact on subsequent NMT sprint performance. Researchers had previously concluded that two familiarisation sprint sessions or 10 to 20 sprint trials should be sufficient to ensure NMT learning effects were accounted for (Morin et al., 2010; Sirotic & Coutts, 2008). Hopker et al. (2009) proposed that three familiarisation sessions could be required, although this was based on a study involving only one maximal treadmill sprint during each session. The findings of this study confirm that a second familiarisation session is redundant if suitable warm-up, testing and data processing techniques are followed.

During the start phase all kinetic variables except mean F_v had unacceptable intra-day reliability, so it seems the inter-trial variability of kinetic outputs during the first two steps is too high to enable useful interpretation and comparisons. During the acceleration and maximum velocity phases all kinetic and kinematic variables had at least moderate intra-day reliability (ICC ≥ 0.75 or CV ≤ 10%) except FT, which was only acceptable during the maximum velocity phase.

Previously reported issues with reliability of NMT data was associated with insufficient familiarisation (Hopker et al., 2009), a rolling sprint-start (Hopker et al., 2009), testing of a youth sample (Rumpf, 2012) and analysis of arbitrary time windows or an entire sprint (Sirotic & Coutts, 2008). In fact, all previous studies that involved analysis of specific sprint steps, with an adult population, have reported acceptable levels of reliability (Cross et al., 2014; Morin et al., 2010; Yanagiya et al., 2003; Yanagiya et al., 2004). The results of this study highlight unacceptable reliability of certain NMT-derived variables during the start phase (peak values for F_v, F_h and horizontal power) and acceleration phase (FT only), even when stepwise analysis of the data was used. Practitioners should be aware of these specific limitations when interpreting NMT data.

In practice the best sprint trial is often monitored to gauge speed performance changes over time (Al Haddad et al., 2015), however the average of two or three sprints was recently reported to be a more reliable method when using radar technology to assess sprint performance (Simperingham et al., 2019). The same conclusions can be made from the findings of this study, where several variables had unacceptable inter-day reliability when the first or best trial was compared between days, while inter-day reliability was at least moderate for all variables when the average of two trials was analysed. Some variables had acceptable inter-day reliability when the first or best trial was used, so practitioners should consider the key variables to be analysed when deciding on the ideal method of summarising NMT data. However, it is the recommendation of the authors that averaged data should be the preferred method used by practitioners.

It should be noted that the participants were young team sport athletes with limited structured speed training experience. It may be hypothesised that athlete biological variation could be less for more highly trained athletes. The reliability results reported relate to the specific data collection and data processing methods used. Alterations to the data collection and processing methods will likely impact on reliability. Typical error associated with a sprint test should be less than the smallest worthwhile change in order to have confidence in drawing conclusions about small changes in performance (Hopkins, 2004). While reliability was determined to be moderate or acceptable for many variables in this study, it should be highlighted that inter-day typical error (CV) was greater than the smallest worthwhile change for all variables except SL, SF, acceleration phase PP, acceleration phase peak F_h and maximum velocity phase peak F_h. This finding may have sample size implications for researchers and practitioners using NMT data to detect small changes in sprint performance.

Conclusions

NMT-derived kinematic and kinetic descriptors of short-distance sprints tended to have moderate or acceptable inter-day reliability: after one treadmill familiarisation session; during the acceleration phase and the maximum velocity sprint phases, but not the start phase; and when results were averaged over at least two trials, rather than comparing single or best trials. Practitioners should adhere to all relevant recommendations (e.g. stepwise post-processing techniques) to optimise reliability and to take advantage of the benefits of NMT technology to measure short-distance sprint performance.

SECTION 2

REVIEWING WEARABLE RESISTANCE AND SPRINT TRAINING OPTIONS

CHAPTER 5

LOWER BODY WEARABLE RESISTANCE TRAINING AND SPRINT-RUNNING: A NARRATIVE REVIEW

Prelude

The reliability of measuring horizontal force, velocity and power during sprint-running was reviewed and tested in Section 1 of this thesis. After one familiarisation session and if the average of multiple sprint trials was used, then almost all NMT-derived kinematic and kinetic variables had acceptable reliability during the acceleration phase and the maximum velocity phase, but not during the start phase (steps 1-2). Similarly, most radar-derived variables tended to have acceptable reliability if the average of two trials was analysed. The variables and protocols proven to be reliable in Section 1 will be used in Sections 3 and 4 to quantify acute and chronic changes in sprint performance. The following section involves reviewing WR and specific sprint training options in order to identify gaps in the literature that will be addressed in subsequent sections. The aim of Chapter 5 was to provide an overview of WR research and specifically to summarise and critically appraise all research into the effects of lower body WR on sprint performance. This synthesis of knowledge identified gaps and provided focus for ensuing chapters. The abstracts of five published journal articles (cited in the following chapter) are included in the Appendices (Appendices G-K). The author of this thesis was a research supervisor and co-author for these publications during the period of PhD enrolment.

Introduction

WR training involves attaching external loads to the body during sporting movements such as jumping, running, sprinting, swimming and cycling (Macadam, Simperingham, & Cronin, 2017). Probably due partly to the popularity and accessibility of weighted vests, a substantial proportion of WR training research has traditionally focused on the effects of upper body loading (Barnes et al., 2015; Bosco, 1985; Bosco et al., 1986; Cross et al., 2014; Faigenbaum et al., 2006). Recent advances in WR technology (e.g. the Lila™ Exogen™ compression-based suit) have greatly increased the flexibility of WR loading placements and increments of magnitude (Figure 8). WR can now easily be attached with Velcro to any aspect of the lower leg, upper leg, torso, or arms in incremental magnitudes of 0.1 kg. The increased options for specifically targeting the loading on the muscles primarily involved in jumping, running and sprinting has led to more recent WR research interest focusing on the effects of lower body WR training, as well as the difference between upper and lower body loading configurations (Couture et al., 2018; Macadam, Simperingham, & Cronin, 2017; Macadam, Simperingham, Cronin, Couture, & Evison, 2017).

The degree of training specificity required to optimise transfer of training to sporting performance is an area of ongoing debate (Brearley & Bishop, 2019; Dylan G, John P, Aaron J, Robert W, & Michael H, 2019). Various models of training transfer have been proposed (Bondarchuk, 1986; Bosch, 2016; Siff & Verkhoshansky, 1993). Siff and Verkhoshansky (1993) proposed five key aspects that should be considered to optimise training transfer in their theory of "dynamic correspondence": amplitude and direction of movement; accentuated regions of force production (specificity of muscular effort and force application); dynamics of the effort; rate and time of maximal force production; and the regime of muscular work. Bosch (2016) proposed that training transfer would be optimised if the training task and the sporting performance (or "target task") have similarity of: intramuscular and intermuscular coordination; sensory input (environment and body); and, movement intention. WR enables light loading of movements directly, thus ensuring similarity of training and target movements. Theoretically the transfer of training with WR should be high if the movement variations with loading are not too drastic compared to unloaded target movements (Bosch, 2016; Brearley & Bishop, 2019).

The effects of WR training during walking, jumping, running and sprint-running were summarised by our research group in a thorough systematic review (Macadam, Cronin, et al., 2017). The present narrative review will incorporate some more recent WR articles that have been published since the systematic search was completed in November 2015. Additionally, two recent review articles have focused specifically on the effects of WR on sprinting (Feser, Macadam, & Cronin, 2019; Macadam, Cronin, Uthoff, & Feser, 2018). The aim of the current review was to extract learnings from the body of general WR research, and then to specifically review all of the cross-sectional and longitudinal studies involving the assessment of lower body WR training in relation to sprinting performance. Key learnings from studies of upper body WR training during running and sprinting are discussed first, and then key findings from studies comparing upper body and lower body WR during running and jumping. These related studies provide context for the relatively low total number of studies focusing on lower body WR and sprinting. (N.B. Published articles that are included as subsequent chapters in this PhD thesis were excluded from this narrative review). Changes in sprint performance and sprint biomechanics are discussed as either acute changes or chronic/longitudinal changes. Acute changes with WR relate to statistically significant ($p \leq 0.05$) intra-session changes compared to baseline unloaded sprinting that occur either while wearing WR, or within several minutes after the external loading is removed. Chronic or longitudinal changes relate to longer lasting effects that are measured after a period of training (e.g. after a six-week training intervention). Throughout the review ‘functional’ kinetic values are calculated relative to body mass, and ‘effective’ kinetic values are calculated relative to total system mass (i.e. body mass plus added WR).

Figure 8. Compression-based WR suit with 0.2 kg loads attached with Velcro.

Upper Body Wearable Resistance Training

Early studies of upper body WR training included reports of significantly increased vertical jump performance (24%) in well trained track and field athletes after wearing weighted vests (11 to 13% of BM) throughout the day for three weeks (Bosco, 1985; Bosco et al., 1986). This form of extended use of WR was termed “simulated hypergravity”. The effect on sprinting speed was unfortunately not reported. When equivalently loaded vests were worn for eight days, sprinting speed was not significantly altered within a group of rugby players (Barr, Gabbett, Newton, & Sheppard, 2015), but a small (2%) improvement in 37 m speed was reported when loaded vests were worn for 3 weeks (eight hours a day, four days per week) with a sample of active males (Scudamore et al., 2016). The simulated hypergravity results are encouraging, particularly given the internationally competitive level of the participants in the study of Bosco et al. (1986), but wearing WR throughout the day is not a sustainable long-term training strategy and results tended to return towards baseline within three to four weeks of the cessation of the training period (Bosco et al., 1986; Scudamore et al., 2016). Improved understanding of the effects of a more limited dose of WR worn only during a training session is likely to be practically more useful and easier to implement.

Conclusions from analysis of upper body WR during treadmill sprinting included that heavy (22% BM) weighted vests resulted in increased F_v, but provided little as a horizontal-vector training stimulus (Cross et al., 2014). It should be noted that a limitation of the study was that the kinetic data was only reported in absolute terms, rather than relative to BM or total system mass (i.e. BM plus WR magnitude). In fact, if the results were expressed relative to total system mass, maximum and average vertical GRF was reduced on average by 8-11%. Additional acute changes with heavy vest loading (5-20% BM) included significantly slower short (≤ 50 m) sprint times (-4 to -12%), increased CT (up to 25%) and decreased FT (up to -27%), while maximum velocity phase SL was 4% lower, but only during treadmill sprints (Cronin, Hansen, Kawamori, & McNair, 2008; Cross et al., 2014; Konstantinos et al., 2014). So, while heavy vest loading is associated with a significant alteration in sprint kinematics, there is no objective evidence of the vertical GRF overload that may be expected with this form of loading. The likely explanation proposed by Cross et al. (2014) was that the maximum vertical displacement was reduced during the significantly shorter flight times with upper body loading, thus leading to an increase in absolute F_v of less than the magnitude of the added vest load (i.e. a decrease in effective F_v relative to total system load). Longitudinal training studies with heavy vest loading have led to chronic improvements in sprint performance of up to 9% (Rey, Padron-Cabo, & Fernandez-Penedo, 2017; Scudamore et al., 2016), but other authors have reported no significant ($p < 0.05$) training effect (Barr et al., 2015; Clark, Stearne, Walts, & Miller, 2010; Rantalainen, Ruotsalainen, & Virmavirta, 2012). A limitation of the upper body WR research is that no studies to date have included analysis of either acute or chronic changes in sprint kinetics during over-ground sprinting, or changes in sprint performance with upper body loads < 5% BM.

A series of stride outs while wearing a 20% BM weighted vest resulted in acutely increased leg stiffness (20%) and acutely improved running economy (6%) when the WR was removed (Barnes et al., 2015). Subsequently peak running speed was improved (3%) during an incremental treadmill running test. Leg stiffness also plays a major role in sprint performance (Bret et al., 2002; Chelly & Denis, 2001), however the acute performance enhancement effect of priming with such heavy upper body WR has not been reported in relation to sprinting. Faigenbaum et al. (2006) reported no significant change in sprint performance following a dynamic warm-up with lighter (2 to 6% BM) weighted vests. However, the sprint test was 10 to 12 minutes after the dynamic warm-up, so it is possible that any acute enhancement effects may have dissipated before the sprint performance was assessed. The review of Sale (2002) described the time course of fatigue and potentiation that occurs after a conditioning stimulus. Theoretically speed performance may be acutely enhanced if fatigue dissipates faster than potentiation (or other causes of performance enhancement) decay following a conditioning activity. However, the majority of applied research in the area has focused on the interaction of fatigue and speed or power enhancement following a heavy resistance exercise such as a back squat (Bevan et al., 2010; Comyns, Harrison, Hennessy, & Jensen, 2007). More research is warranted, specifically addressing the optimal rest periods for acute performance enhancement of sprinting following lighter, ballistic pre-conditioning stimuli (Maloney, Turner, & Fletcher, 2014).

Upper Body vs Lower Body Wearable Resistance Training

Authors that reported a significant impact of upper body WR on sprinting and running have tended to use loading magnitudes of 11 to 23% BM (Barnes et al., 2015; Bosco, 1985; Bosco et al., 1986; Cross et al., 2014). It may be hypothesised that lighter loading could still result in significant changes in jumping, running and sprinting when the WR is attached directly to the limbs rather than the torso. Whilst vest loading provides a vertical loading stimulus (although as mentioned above, typically results in a reduction in effective F_v), direct loading of the limbs provides both a vertical and rotational loading stimulus. In fact, loading of only 2% BM when attached to the forearms resulted in a significant reduction in running velocity (-1%) as well as a significant change (2-7%) in sprint biomechanics (Macadam, Simperingham, & Cronin, 2019). It would be expected that a similar proportional increase in the rotational moment of inertia of the lower body would have an even greater impact on jumping, running and sprinting given that the lower body is primarily involved in producing the movement.

Macadam, Simperingham, Cronin, et al. (2017) compared the effects of upper and lower body loading of up to 6% BM during vertical jumping, while Couture et al. (2018) compared the effects of upper and lower body loading of up to 5% BM during constant pace running (14 km/h). Counter-movement jump height, peak power and peak velocity were all significantly lower, even with WR of 3% BM, compared to unloaded jumping (Macadam, Simperingham, Cronin, et al., 2017). There was, however, no significant difference between the effects of upper body and lower body WR during vertical jumping. Decreased jump height due to the WR resulted in decreased vertical landing forces (due to the reduction in gravitational acceleration) regardless of loading placement. The reduction in vertical GRF with upper body WR was -9% and the reduction with lower body WR was -5%, but the difference was not statistically significant ($p > 0.05$). It may be that the contribution of rotational overload due to lower body WR compared to upper body WR during jumping is relatively similar considering the similar ranges of motion of the lower and upper body during the jumping movements. During running and sprinting however, the range of motion of the lower body is substantially different to that of the upper body, so a differential impact of lower body compared to torso loading is expected.

Step kinematics (CT, FT, SL and SF) were not significantly altered during constant pace running with loading of ≤ 5% BM when attached to either the upper body or the lower body (Couture et al., 2018). CT (3%) and FT (-5%) were only significantly changed with whole body loading of 10% BM (i.e. 5% BM on the lower body combined with 5% BM on the upper body). In contrast to the vertical jump findings there was a significant difference when the WR was attached to the lower body compared to the upper body during running. Effective and functional propulsive GRF and propulsive impulse were significantly higher (3-4%) when the WR was attached to the lower body compared to the upper body. The authors suggested an explanation to be the increased rotational inertia caused by attaching the equivalent magnitude of loading to the rapidly moving lower limbs instead of the torso. The movement of the upper body in the frontal plane is relatively minimal during running, so the contribution of rotational overload from the vest loading would also be minimal. No sprint studies to date have included a direct comparison of the same magnitude of WR attached to the lower body compared to the upper body. Ropret et al. (1998) reported a greater decrease in sprint velocity with load attached to the lower shank compared to handheld loads, however the loads were not of equivalent magnitude (i.e. more WR was attached to the lower body than the upper body).

Lower Body Wearable Resistance Training and Sprint-Running

The acute effects of WR during sprinting are summarised in Table 11 for light (≤ 2% BM), moderate (3 to 4% BM) and heavy (≥ 5% BM) lower body WR (Feser, Macadam, Nagahara, & Cronin, 2018; Hurst, Kilduff, Johnston, Cronin, & Bezodis, 2018; Macadam, Simperingham, & Cronin, 2017; Ropret et al., 1998; Zhang, Yu, & Liu, 2018). Downward arrows indicate a statistically significant decrement in speed/velocity performance. For all other variables a downward arrow indicates a statistically significant decrease, while an upward arrow indicates a statistically significant increase. Eighty-six participants were included across the six studies, but only two females. Participants included sprinters (Feser et al., 2018; Hurst et al., 2018; Zhang et al., 2018), beach sprinters (Bennett, Sayers, & Burkett, 2009), rugby players (Macadam, Simperingham, & Cronin, 2017) and students (Ropret et al., 1998). Only one study to date has included an assessment of the chronic changes in sprint performance to occur after a lower body WR training intervention (Pajic, 2011).

The acceleration phase and the maximum velocity phase of sprint-running are biomechanically different (Mann, 2011; Nagahara et al., 2019; Nagahara et al., 2014; von Lieres Und Wilkau et al., 2018; Yu et al., 2016), so it is important to consider separately the effects of light, moderate and heavy lower body WR on the two sprint phases. The acceleration phase is characterised by a forward leaned body position and a linear, “piston-like” pumping action of the legs where the GRF is directed in a horizontal direction as much as possible (Hunter et al., 2005; Kawamori, Nosaka, et al., 2013; Konstantinos et al., 2014; Rabita et al., 2015). The maximum velocity phase involves a more upright body position with a more circular “pendulum-like” leg motion where improved performance is associated with shorter ground CT, longer SL and higher vertical stiffness (Bret et al., 2002; Chelly & Denis, 2001; Kugler & Janshen, 2010; Mann, 2011; Nagahara & Zushi, 2017). Debate persists as to whether the horizontal or vertical component of the GRF is most important in achieving faster running speeds during the maximum velocity phase

(Brughelli et al., 2011; Morin et al., 2012; Nagahara et al., 2019; Nummela et al., 2007; Weyand et al., 2000). Horizontal and vertical GRF are not independent variables, but instead are the two key components of the resultant GRF (F_{TOT}), with the medial-lateral GRF component considered to have little influence on sprint performance. Given the important contribution of both vertical and horizontal GRF during sprinting, a thorough understanding of the impact of WR on these kinetic determinants of sprinting will assist in individualising WR training programs to the specific needs of athletes. For the purposes of this narrative review, sprints of up to 20 m will be considered representative of the acceleration phase, while maximum intensity sprints of greater than 20 m will be used to represent the maximum velocity phase.

The majority of studies of the effects of lower body WR during sprinting have utilised light to moderate loading (≤ 3% BM) with a variety of attachment locations including distal shank (Ropret et al., 1998), mid shank (Feser et al., 2018; Hurst et al., 2018; Zhang et al., 2018), thigh (Feser et al., 2018; Hurst et al., 2018), or whole leg (i.e. combined shank and thigh loading) (Bennett et al., 2009; Macadam, Simperingham, & Cronin, 2017). Only one cross-sectional study (Ropret et al., 1998), and one longitudinal training study (Pajic, 2011) assessed the effects of heavy (5% BM) lower body WR, both using a distal shank loading placement.

Table 11. Acute changes in sprinting speed, kinematics and kinetics during the acceleration and maximum velocity sprint phases with light (≤ 2% BM), moderate (3 to 4% BM) and heavy (≥ 5% BM) lower body WR. Load placement are separated into: (i) whole leg (thigh and shank), (ii) thigh, and (iii) shank placements.

			Light WR (≤ 2% BM)			**Moderate WR (3-4% BM)**			**Heavy WR (≥ 5% BM)**		
			Whole Leg	***Thigh***	***Shank***	***Whole Leg***	***Thigh***	***Shank***	***Whole Leg***	***Thigh***	***Shank***
Acceleration Phase (0-20 m)	**Speed**	0-10 m	↔	↔	↔	↔					
		0.5-15 m			↓ 3.6%			↓ 4.6%			↓ 7.8%
		10-20 m	↓ 4.2%			↓ 2.2-2.9%					
		V0				↓ 5.4-6.5%					
	Kinematics	CT		↔	↔	↑ 3.4-6.0%					
		FT		↔	↔	↔					
		SL		↔	↔	↔					
		SF		↔	↓ 2.1%	↓ 2.0-3.0%					
	Kinetics	F_v									
		F_h									
		F0				↔					
		S_{Fv}				↓ 9.9-12.0%					
		Pmax				↔					
Maximum Velocity Phase (≥ 20 m)	**Speed**	15-30 m			↓ 4.2%			↓ 8.5%			↓ 12.8%
		20—30 m	↔								
		30—40 m	↓ 7.4%								
		40 m	↔								
		50 m		↔	↔						
		vmax		↓ 1.8%	↓ 1.4-2.3%						
	Kinematics	CT	↔ (↑8.9%)	↑ 2.5-2.9%	↑ 1.2-2.1%						
		FT	↔	↔	↑ 2.8-3.3%						
		SL		↔	↔						
		SF	↔	↓ 1.4-3.7%	↓ 2.3%						
	Kinetics	F_v									
		F_h									
		F0									
		Pmax									

Note. Compared to unloaded sprinting: ↓ = a statistically significant decrement (sprinting speed) or decrease; ↑ = a statistically significant increase; WR = wearable resistance; BM = body mass; V0 = theoretical maximum velocity; CT = contact time; FT = flight time; SL = step length; SF = step frequency; F_v = vertical ground reaction force; F_h = horizontal ground reaction force; F0 = theoretical maximum horizontal force; S_{Fv} = slope of the force-velocity profile; Pmax = maximum horizontal power output

Acceleration Phase

Light to moderate lower body WR (≤ 3% BM) typically resulted in no significant change in acceleration phase sprint times over the initial 10 m (Bennett et al., 2009; Feser et al., 2018; Macadam, Simperingham, & Cronin, 2017), but sprint times were significantly slower (-3 to -4%) in the 10 to 20 m section of acceleration (Bennett et al., 2009; Macadam, Simperingham, & Cronin, 2017). Between 1 and 2% BM WR positioned on the shank resulted in significantly lower SF, but acceleration sprint velocity appears (from the results figure in Ropret et al. (1998)) to only be lower with the distal shank load positioning and not with mid shank positioning (Feser et al., 2018). When the WR (2 to 3% BM) was spread over the whole leg, researchers also reported lower SF (-3%), as well as longer acceleration phase CT (3%) (Bennett et al., 2009; Macadam, Simperingham, & Cronin, 2017). In addition to no significant change in 0-10 m sprint times with lower body WR, there were also no significant changes in acceleration phase FT or SL in the studies that measured these variables (Bennett et al., 2009; Feser et al., 2018; Macadam, Simperingham, & Cronin, 2017). Ropret et al. (1998) reported on the effects of heavy (5% BM) lower body WR, but did not assess FT, CT or changes in kinetic variables. Further research is required to establish if the same patterns of acceleration phase changes hold with heavy lower body WR.

In the only assessment of the impact of lower body WR on kinetic variables, Macadam, Simperingham, and Cronin (2017) reported no change in maximum horizontal force or power, but there was a significant change towards a more force dominant force-velocity profile. Kinetic data was derived from high frequency horizontal velocity data sampled from a radar device (Simperingham et al., 2019). It seems that sprinting with lower body WR may be a particularly suitable training option for those individuals identified as having a relatively velocity-dominant force-velocity profile (Morin & Samozino, 2016). Those athletes may tend to benefit from the inclusion of more force-oriented sprint training options, such as training with WR. Evidence of a chronic change in the slope of the force-velocity relationship towards a more force-dominant profile after a longitudinal WR training intervention is necessary to support this training hypothesis.

Maximum Velocity Phase

Ropret et al. (1998) reported a 13% decrease in maximum velocity with lower body loading equivalent to approximately 5% BM attached just above the ankle (i.e. 2.5% BM per leg). All other assessments of lower body WR during the maximum velocity phase of over-ground sprinting involved lighter (≤ 2% BM added weight) and more proximally loaded configurations attached to the shank (Feser et al., 2018; Hurst et al., 2018; Zhang et al., 2018), thigh (Feser et al., 2018; Hurst et al., 2018) or whole leg (Bennett et al., 2009). The light loading on the shank or thigh also resulted in a significant decrease in maximum velocity (≤ 2%) (Feser et al., 2018; Hurst et al., 2018; Zhang et al., 2018), but when the load (equivalent to 2% BM) was spread across the whole leg the decrease in velocity was more than twice as much (5%) (Bennett et al., 2009). This is an unexpected finding as the same magnitude of load positioned more proximally should theoretically have a less noticeable impact on baseline sprinting technique. All participants in the studies were well trained sprinters, so the difference in outcomes does not appear to be due to a difference in the physical characteristics of the participants. Medio-lateral shank loading placement was used in the study of Bennett et al. (2009), but it also seems unlikely that this would cause substantial differences in sprint times between the studies.

When kinematic values were measured during the maximum velocity phase, ground CT was longer (2-3%) and SF was shorter (-2 to -4%) with the WR (Feser et al., 2018; Hurst et al., 2018), although this trend was not significant in the study of Bennett et al. (2009). These changes are reasonably consistent with the acceleration phase changes, but maximum velocity phase FT was also longer (3%) with light shank loading, but not when the load was attached more proximally on the thighs (Hurst et al., 2018). There was no difference in hamstring electromyography (EMG) results during maximal velocity sprinting with light (1 to 2% BM) lower body WR (Hurst et al., 2018). Future research in this area could analyse moderate to heavy loading magnitudes as well as the hip flexor musculature, which is known to be strongly related to sprinting performance (r = 0.69) (Ema, Sakaguchi, & Kawakami, 2018). No studies to date have reported changes in kinetic variables with lower body WR during the maximum velocity phase. Understanding the acute changes in horizontal and vertical GRF with lower body WR will help to ensure suitable and safe WR overloads are used during training sessions.

Load Placement

No significant ($p > 0.05$) kinematic or kinetic differences were observed between 3% BM lower body loading positioned on the anterior aspect of the legs compared to the posterior aspect of the legs (Macadam, Simperingham, & Cronin, 2017). However, analysis was limited to acceleration phase kinematics and radar-derived sprint variables. Future research could include analysis of changes in joint angles, joint torques or muscle activation with various load placements. Feser et al. (2018) compared proximal (thigh) and distal (shank) loading placements with 2% BM WR. The only difference between the loading positions was maximum velocity phase FT, which was unchanged with the proximal positioning compared to unloaded sprinting ($p > 0.05$), but was increased (3%) with the distal positioning. The increased rotational inertia created by the more distal load placement would have caused the increased overload and subsequent alteration to baseline sprinting biomechanics. It seems there is a threshold of overload that the body can absorb without significantly altering biomechanics. Overload can be increased by increasing the magnitude of the load or by moving the loading placement relatively more distally. In contrast, FT was not significantly changed during the acceleration phase, presumably due to the same magnitude of load providing less rotational overload during the more linear, pumping action of the legs during acceleration.

Longitudinal Effects

Pajic (2011) assessed the impact of six weeks of training three times per week with heavy lower body WR (5% BM). The speed intervention involved a progressive overload from one set of five 50 m sprints in weeks 1-2, to two sets in weeks 3-4, and finally three sets in weeks 5-6. Maximum velocity was not significantly changed after the training intervention, but SL was significantly longer (5%) and SF was significantly lower (-6%). Maximum velocity is the product of SL and SF and a negative interaction is known to exist between the two variables (Mackala, 2007; Nagahara et al., 2014), so it is difficult to improve speed by increasing both of these variables.

Significant changes in two-dimensional knee joint angles indicated a change towards a more upright and possibly stiffer running posture after the WR training intervention (Pajic, 2011). Increased vertical stiffness after training could have a positive impact on sprint performance, however stiffness was not calculated. The chronic effects on acceleration performance and related kinematic and kinetic variables were also not analysed, so there is broad scope for improving the understanding of this area with further training studies combined with thorough analysis of the impact on both acceleration phase and maximum velocity phase sprint kinematics and kinetics.

Conclusions

Light to moderate lower body WR tends to be well tolerated during the first 10 m of acceleration, however sprint velocities are reduced for sprints > 10 m. A similar pattern of increased ground CT and decreased SF was reported in most assessments of either the acceleration phase or the maximum velocity phase. Changes in sprint kinetics with lower body WR have not been comprehensively explored. A clearer understanding of the changes in acceleration phase and maximum velocity phase sprint biomechanics with lower body WR is necessary to prescribe optimal sprint training interventions. Future research into this area should include: a comparison of upper body and lower body WR loading configurations; thorough biomechanical analysis (including kinematic and kinetic data and three-dimensional analysis) during acceleration phase and maximum velocity phase sprinting with light, moderate and heavy lower body WR (1-5% BM); assessment of the potential for acute enhancement of sprint performance after an acute intervention involving lower body WR; and finally, well controlled longitudinal interventions are needed to determine if there are benefits to training with lower body WR above traditional unloaded sprint training.

CHAPTER 6

ACUTE EFFECTS OF LOADED AND UNLOADED BALLISTIC EXERCISE ON SPRINT-RUNNING PERFORMANCE

This paper comprises the following paper prepared for *European Journal of Sport Science*:

Chapter 6. Simperingham, K. D., Macadam, P., Cronin, J. B. & Ross, A. (2019). Acute effects of loaded and unloaded ballistic exercise on sprint-running performance: a systematic review. *European Journal of Sport Science [In preparation]*.

Prelude

The seven studies (including one longitudinal study) that contributed to the understanding of the effects of WR training on speed training with lower body WR were summarised and analysed in the previous chapter. Initial sprinting speed was not significantly altered by WR, but for sprint distances > 10 m, sprint velocity was up to 8% slower in the acceleration phase and up to 13% slower in the maximum velocity phase compared to unloaded sprinting. Step kinematics were significantly changed in the acceleration phase with moderately (3-4% BM) loaded WR, or distally positioned light (≤ 2% BM) loads. Substantial gaps in the sprint literature remain regarding the kinematic changes with heavy WR, the kinetic changes at any loading level and sprint phase, and the maximum velocity phase changes with moderate WR. The identified gaps will be addressed in Section 3, however before that it is important to broadly explore a potentially useful practical application of WR training – the acute performance change effects of contrast loading with WR. While the previous chapter analysed the changes in sprint performance that occurred while acutely wearing WR or after a period of several weeks of training with WR, the next chapter assesses the within session impact of loaded and unloaded ballistic exercise (BE; including jumps, loaded sprints, loaded dynamic warm-ups and explosive power cleans) on subsequent unloaded sprint performance. The effects immediately after a ballistic exercise and up to 30 minutes later will be summarised and compared. Unloaded ballistic exercises were included in the review to improve the general understanding of the learnings to date with this training application and due to the relatively low number of studies in the area to date with ballistic exercise and added WR. The key outcomes were to estimate optimal rest period lengths between ballistic exercise and sprint performance to inform practical applications for athletes and coaches, and to inform the WR speed training program used in Chapter 12.

Introduction

Ballistic exercise is characterised by the intent to accelerate a mass (e.g. body mass (BM)) throughout an entire movement with maximal velocity and usually involves projection of a body or an external object (McMaster, Gill, Cronin, & McGuigan, 2014; Newton, Kraemer, Häkkinen, Humphries, & Murphy, 1996). Ballistic exercises include jumping, throwing, sprinting and modified Olympic lifting (Maloney et al., 2014), all movements commonly incorporated into training programs with the goal of improved speed and power production (Lockie et al., 2012; Rumpf et al., 2016). Ballistic exercises do not contain the braking phase associated with traditional resistance exercise (Maloney et al., 2014) and may increase the relative duration of positive acceleration which thereby facilitates greater force output and muscle activation (Newton et al., 1996). Moreover, ballistic exercise is associated with the preferential recruitment of type II motor units (Desmedt & Godaux, 1977). The chronic benefits of ballistic training for improving sprinting speed are well established in the literature (Lockie et al., 2014; Rimmer & Sleivert, 2000). Increasingly research attention is also focusing on the potential for ballistic exercise to elicit an intra-session acute enhancement of sprint and power performance (Maloney et al., 2014; Seitz & Haff, 2016).

Speed and power training recommendations traditionally involved avoiding residual fatigue from prior endurance and strength training and training in a fresh state (Newton & Kraemer, 1994). There is however evidence of improved speed and power performance between several minutes and several hours after activities such as heavy resistance exercise (Bevan et al., 2010; Comyns et al., 2007; Cook, Kilduff, Crewther, Beaven, & West, 2014; Ebben, 2002; Till & Cooke, 2009), so careful consideration of the order and timing of training sessions is important. Complex training is the technique that involves completing (usually biomechanically similar) pairs of exercises in close succession with the aim of acutely enhancing power performance after a prior conditioning stimulus (Ebben, 2002). While there is evidence of acutely improved sprint performance after a heavy resistance exercise (e.g. 3 repetition maximum back squat) (Bevan et al., 2010; Comyns et al., 2007), the practical utility of this form of complex pair is relatively limited, particularly for field-based sessions. There is growing evidence that ballistic exercise can be used as a conditioning stimulus to acutely enhance subsequent sprint performance (Maloney et al., 2014). Ballistic exercise such as plyometrics and loaded sprints are commonly used within speed training sessions and they represent a practically more useful combination of exercises to include during track or on-field sessions rather than heavy resistance exercises.

The acute improvement in muscular performance characteristics after a conditioning stimulus is commonly referred to as post-activation potentiation (PAP) (Sale, 2002; Suchomel, Sato, DeWeese, Ebben, & Stone, 2016; Tillin & Bishop, 2009). PAP can be induced by a voluntary conditioning contraction, often performed at or near maximal intensity, and has been found to increase both peak force and rate of force development during subsequent twitch contractions (Maloney et al., 2014; Tillin & Bishop, 2009). The proposed mechanisms underlying PAP may be related to the phosphorylation of myosin regulatory light chains, improved recruitment of higher order motor units, and a possible change in pennation angle (Sale, 2002; Tillin & Bishop, 2009). While PAP relates to improved nerve impulses, it has also been proposed that improved power performance after a conditioning stimulus may be caused by other influential changes such as leg stiffness and tissue temperature (Comyns et al., 2007; Maloney et al., 2014; Seitz & Haff, 2016). To take account for the range of possible reasons for performance changes following a conditioning stimulus (e.g. thermogenic, hormonal, neural, psychological) the term acute performance enhancement (APE) will be used instead of PAP for the remainder of this review.

Theoretically, both fatigue and acute enhancement will peak directly after a conditioning stimulus (Sale, 2002). Therefore, an APE effect will only be observed if fatigue dissipates faster than the acute enhancement effects (Figure 9). The optimal rest period length for sprinting APE effects will be dependent on the type and intensity of the conditioning stimulus, the type of sprint (i.e. acceleration vs maximum velocity), and individual descriptors such as training status, muscle fibre type composition and muscle temperature (Maloney et al., 2014; Seitz & Haff, 2016; Turner, Bellhouse, Kilduff, & Russell, 2015). Assuming the fatigue effects are less with ballistic exercise compared to heavy resistance exercises, the APE time course will be shortened (Figure 9).

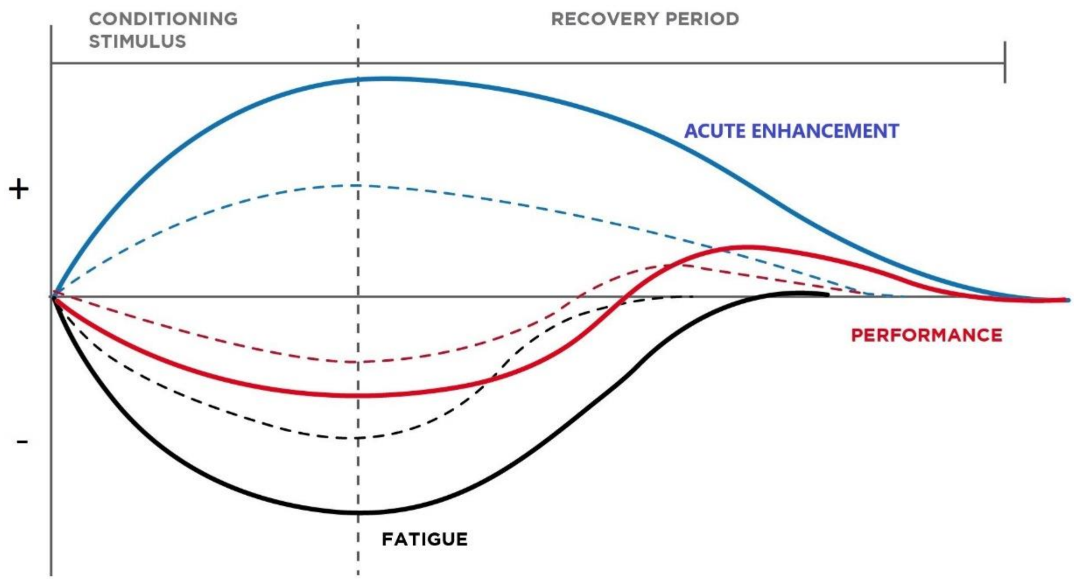

Figure 9. Theoretical interaction of fatigue (black lines), acute enhancement (blue lines) and performance (red lines) following a heavy resistance exercise conditioning stimulus (solid lines) or a ballistic exercise conditioning stimulus (dashed lines).

The two key phases of sprint-running are the acceleration phase and the maximum velocity phase, which are determined by a combination of specific physiological, metabolic and biomechanical factors (Buchheit et al., 2014; Mann, 2011). As such, it is likely that the ideal ballistic exercise pre-conditioning stimulus may be different if the goal of APE is to enhance sprint performance in the acceleration phase or the maximum velocity phase. The aim of this systematic review was to summarise all APE research that involved a ballistic exercise conditioning stimulus combined with the outcome measure of subsequent sprint performance. Key outcomes were to estimate optimal rest period lengths between ballistic exercise and sprint performance to inform practical applications of the research. Factors that may modify the APE effects as well as gaps in the literature were identified.

Literature Search Methodology and Study Selection

A systematic search of the research literature was undertaken for studies assessing the APE effects of loaded and unloaded ballistic exercise on sprint-running performance. The following electronic databases were searched between May 1, 2017 and September 1, 2017: Web of Science, PubMed and SPORTDiscus. The following keywords were used during the electronic searches: (sprint* OR run* OR acceleration OR velocity) AND (ballistic OR plyometric OR resist* OR vest OR load OR weight* OR sled OR underspeed) AND (PAP OR potentiation OR enhance*). Additional studies were found by reviewing the reference lists from retrieved studies.

Articles were included that used a ballistic exercise conditioning stimulus (e.g. jump, bound, sprint and power clean) and that quantified a sprint performance outcome measure. Loaded dynamic warm-ups involving ballistic exercise were included. Heavy resistance exercises (e.g. back squat) were not included. Studies included original research on healthy subjects that were published in peer-reviewed journals. No age or sex restrictions were imposed during the search stage. Studies were limited to the English language.

The searches identified 2,921 potentially relevant articles: Web of Science (657 articles), PubMed (1682 articles) and SPORTDiscus (582 articles). Following a review of titles and abstracts, the total was reduced to twenty-nine. After applying the inclusion and exclusion criteria nineteen studies were retained for further analysis. Significant differences were reported from studies at an alpha level of $p < 0.05$. Effect sizes (ES) were reported when provided in the studies. ES were classified as trivial (0-0.19), small (0.20-0.59), moderate (0.60-1.19), and large (1.20-1.90) (Hopkins et al., 2009).

Literature Search Results and Study Characteristics

Findings from nineteen studies are summarised in Table 12. Subjects were described by the authors as physically active, athletically trained, strength trained or international level athletes with an age range of 15 to 29 years. Ballistic exercise included countermovement jump (CMJ) (1 study), drop jump (DJ) (one leg or two legs; 4 studies), squat jump (SJ) (1 study), tuck jumps (1 study), hops or bounds (one leg or two legs; 3 studies), power cleans (2 studies), sled-resisted sprints (6 studies), pulley resisted/assisted sprints (1 study), WR (1 study) and dynamic warm-ups (which included sprints, jumps and skips as warm-up exercises; 2 studies). The rest interval prior to speed testing ranged from 15 seconds to 30 minutes, while the sprint-running distance ranged from 9 to 60 m. Of note, the results from two studies (Lockie et al., 2016; Simperingham, Cronin, Pearson, & Ross, 2015) are case studies and therefore do not contain statistically significant findings but descriptive changes.

Acute Changes in Sprint-Running Performance after BE

The Effects of Jumps and Bounds

A wide range of rest periods (15 seconds to 16 minutes) were found to elicit significant improvements (1-5%) in sprint-running following jumps or bounds (Table 13). A simple intervention of unloaded drop jumps (DJ) was effective at producing a 3-5% APE effect during the acceleration phase one minute after three DJ repetitions (Byrne, Kenny, & O'Rourke, 2014), and over 50 m (i.e. combined acceleration phase and maximum velocity phase sprinting) 10 and 15 minutes after 10 DJ repetitions (Bomfim Lima et al., 2011). In contrast, Dello et al. (2016) reported a decrement in 20 m sprint performance 16-30 minutes after three sets of 10 DJ within an adolescent population (approximately 15 years old). It should be noted that the same authors recorded significantly reduced counter-movement jump performance even within the walking control group.

In a case study, Lockie et al. (2016) reported acceleration phase sprint time improvements of 1.0-2.1%, 2-16 minutes after completing 30 unloaded alternate leg bounds. Turner et al. (2015) tested a larger group of participants after the same bounding intervention and only found ACCEL improvements (1.2-1.4%) after 4 minutes of rest with unloaded bounding and 2.1-2.9% improvements with 10% BM loaded bounding after 4-8 minutes of rest. The case study of Lockie et al. (2016) was the only other study to report an APE of acceleration phase sprint performance (1-2%) after loaded jumps when squat jumps (15 repetitions at 30% of 1 repetition maximum back squat load) were combined with a rest period of 15 seconds to 12 minutes .

No significant improvements were reported in studies that used tuck jumps, loaded CMJ or two-legged repetitive bounds prior to sprint-running (Dello et al., 2016; Kümmel et al., 2016; Mcbride, Nimphius, & Erickson, 2005; Till & Cooke, 2009). Ten pogo jumps immediately prior to 30 m sprints did not positively impact sprint performance, but in addition to the very short rest period (10 seconds), the conditioning stimulus was biomechanically very different to the acceleration phase sprint. It would be of interest to assess the impact of the pogo jumps after a longer period of rest and on the maximum velocity phase separately, given the established relationship between maximum velocity and leg stiffness (Chelly & Denis, 2001). In the only study to incorporate WR (5% BM) during a pre-conditioning jump (DJ), SL was reduced (-5%) during the acceleration phase, 40 m sprint time was slower (-1%) and vertical stiffness was also substantially lower (-5%) during the maximum velocity phase (Simperingham et al., 2015). It appears the fatigue effects of jumping with WR equivalent to 5% of BM had not sufficiently dissipated after the five-minute rest period. This case study should be repeated with a larger sample of participants and with a longer rest period prior to sprint testing.

Based on the limited number of studies in the area to date (n = 9), the following APE optimal rest period approximate guidelines are proposed:

Unloaded jumps < 10 jump contacts	~1min rest
Unloaded jumps ≥ 10 jump contacts	4-16 min rest
Loaded jumps ≥ 10 jump contacts	4-12 min rest

When the APE target is the maximum velocity phase rather than the acceleration phase, a longer rest period may tend to be optimal. Irrespective of the type or quantity of jumps or bounds, rest periods of greater than 16 minutes appear to have no APE effect on sprint performance. The intensity of jumps can be increased by selecting a different type of jump or increasing intensity of the same movement by changing from bilateral to unilateral jumps, changing the height of a depth jump, or adding external load to the jump movement. As the jump intensity changes the impact on fatigue and the time course of performance changes will alter (Figure 9). The optimal rest period windows above are currently relatively wide to take account of these factors. The strength of these guidelines will be improved with future research including a range of rest period lengths, diverse pre-conditioning stimuli and further maximum velocity phase testing.

The Effects of Resisted Sprints and Loaded Warm-Ups

Eight studies assessed the effects of resisted sprint-running with performance improvements ranging from 1.6-3.3% following rest periods of 5-12 minutes (Table 14). A significant improvement (3.1 ± 1.1%) in acceleration phase sprint-running performance over 15 m was found following a 12 minute rest interval after 75% BM sled sprints, though no improvements were found following the 150% BM sled condition (Winwood, Posthumus, Cronin, & Keogh, 2016). Similarly, a significant improvement in velocity was reported after 8 minutes (1.9%) and 12 minutes (1.6%) with 75% sled push sprints over 20 m (Seitz, Mina, & Haff, 2017). While a significant decrement in 20 m sprint-running performance was found with 125% BM after 15 seconds (-2.7%) and 4 minutes (-2.7%) (Seitz et al., 2017). Sprint time significantly improved (-2.8%) following a 8 minute rest interval with 3 repetitions of 50% BM sled sprints, though no significant improvements were found following 1 or 2 repetitions or after any other rest interval times (Turner et al., 2015). No improvement in sprint performance was reported 5 minutes after sled sprints with 10% BM, or 5 minutes after resisted sprints with a pulley system (Van Den Tillaar, Teixeira, & Marinho, 2017; Van Den Tillaar & Von Heimburg, 2017). Therefore, it can be proposed that rest periods of 8-12 minutes are required following sled resisted sprints with loading of 50-75% BM for an APE of the acceleration phase. In the only study of APE after assisted sprinting, there was no significant change in sprint performance after a 5 minute rest period (Van Den Tillaar & Von Heimburg, 2017).

Lighter loading using WR seems to be more beneficial to the acceleration phase after a 5 minute rest period, though only one case study has been completed to date (Simperingham et al., 2015). No changes in 40 m sprints were found following flying starts over 20 m with WR of 1% BM, while incremental WR over three sets with 1-5% BM resulted in a sprint time improvement of 3.3% at 10 m, but no change at 40 m.

There was no significant change in acceleration phase sprinting 12 minutes after a dynamic warm-up with added upper body loading (2-6% BM weighted vest) (Dello et al., 2016). However, participants were only 15 years old and were required to complete a range of other jump and power tests during the relatively long rest period. Five to fifteen minutes after a dynamic warm-up with lower body WR (3% BM), the sole participant was substantially faster over 10, 30 and 40 m (Simperingham et al., 2015). Speed during the maximum velocity phase was not substantially faster, but kinematic variable changes during the maximum velocity phase included shorter ground CT (-5%), and longer FT (2%) and SF (1%), and greater vertical stiffness (13%). The case study findings are encouraging, however further research is required before proposing empirically based recommendations for APE following a loaded warm-up.

The Effects of Modified Olympic Lifting

Both studies that assessed the APE effects of the power clean used one set of three repetitions at 90% of one repetition maximum as the conditioning stimulus (Table 15). No significant effects were found over a 40 m sprint after a one minute rest (Guggenheimer, Dickin, Reyes, & Dolny, 2009). However, significant improvements in 20 m sprint time (3.1 ± 1.1%) were recorded after a seven minute rest period (Seitz, Trajano, & Haff, 2014). It is not surprising that a one-minute rest period was insufficient to achieve APE, particularly given the likely residual fatigue from the baseline 40 m sprint that was completed only three minutes prior to the post-test sprint. As well as using a longer rest period, Seitz et al. (2014) recruited a strong sample of participants (average one repetition maximum back squat of approximately twice BM), but only measured sprint performance over the acceleration phase.

Until further research is completed in this area, a rest period of approximately seven minutes can be recommended to achieve an APE of the acceleration phase of sprinting following a heavy set of three power cleans.

Factors That May Influence APE Effects

Factors that may influence the APE of sprint performance following a ballistic exercise include: exercise selection, intensity and volume of the ballistic exercise conditioning stimulus as well as the subsequent sprint performance; recovery duration between the ballistic exercise and sprint; and individual characteristics such as gender, training status/age, strength, speed, muscle/body temperature, limb stiffness and muscle fibre type composition (Maloney et al., 2014; Seitz & Haff, 2016; Turner et al., 2015). Nearly half (n = 8) of the studies in this literature review included an assessment of multiple recovery durations, however very few of the authors included analysis of the other potentially influential factors.

There were examples of relatively strong participants achieving APE (Seitz et al., 2014) and relatively weak participants not achieving APE (Till & Cooke, 2009), but no firm evidence about the importance of strength in modulating the APE connection between ballistic exercise and sprinting. In fact, Mcbride et al. (2005) reported no effect of strength, however this was within a group of participants that did not achieve APE.

Table 12. Study characteristics investigating the effect of ballistic exercise on subsequent sprint performance (n = 17).

Study	Subjects	Ballistic exercise intervention	Training volume	Rest time prior to testing	Sprint distance	Sprint performance outcomes
Mcbride et al. (2005)	15 AT males 20.8 ± 1.0 years, 1.84 ± 0.07 m, 100.1 ± 15.5 kg	Smith machine CMJ with 30% of 1RM back squat	1 set x 3 reps	4 min	40 m	No significant effects
Faigenbaum et al. (2006)	18 AT females 15.3 ± 1.2 years, 1.66 ± 0.09 m, 61.6 ± 10.4 kg	Nine dynamic warm-up exercises with 2% BM WV	1 set of 15 min dynamic warm-up (including skips and sprints)	12 min	9.14 m	No significant effects
Faigenbaum et al. (2006)	18 AT females 15.3 ± 1.2 years, 1.66 ± 0.09 m, 61.6 ± 10.4 kg	Nine dynamic warm-up exercises with 6% BM WV	1 set of 15 min dynamic warm-up (including skips and sprints)	12 min	9.14 m	No significant effects
Guggenheimer et al. (2009)	9 AT males 20.6 ± 1.5 years, 1.81 ± 0.06 m, 84.6 ± 17.2 kg	Power clean at 90% 1RM	1 set of 3 reps	1 min	40 m	No significant effects
Till and Cooke (2009)	12 AT males 18.3 ± 0.72 years, 1.76 ± 0.05 m, 72.1 ± 8.0 kg	Tuck jump	1 set x 5 reps	4-6 min	20 m	No significant effects
Bomfim Lima et al. (2011)	10 AT males 20.6 ± 2.6 years, 1.76 ± 0.06 m, 73.7 ± 9.2 kg	DJ from 0.75 m	2 sets x 5 reps	5 min	50 m	No significant effects
				10 min		Sprint time: 2.4% (0.16 s) faster than control (P<0.05, ES=0.66)
				15 min		Sprint time: 2.7% (0.17 s) faster than control (P<0.05, ES=0.69)
Byrne et al. (2014)	29 PA male students 20.8 ± 4.4 years, 1.80 ± 0.06 m, 82.6 ± 9.9 kg	DJ from individual heights 0.2, 0.3, 0.4, 0.5, 0.6 m	1 set x 3 reps	1 min	20 m	Sprint time: 5.0% (0.17 s) faster than control (P=0.001, ES=0.84) Sprint time: 2.9% (0.10 s) faster than dynamic warm-up (P=0.001)

Study	Subjects	Ballistic exercise intervention	Training volume	Rest time prior to testing	Sprint distance	Sprint performance outcomes
Seitz et al. (2014)	13 AT males 18.8 ± 0.9 years, 1.77 ± 0.05 m, 77.1 ± 7.4	Power clean at 90% 1RM	1 set x 3 reps	7 min	20 m	Sprint time: 3.1 ± 1.1% (0.10 s) faster than control (P<0.01, ES=0.92) Velocity: 3.2 ± 1.2% greater than control (P<0.01, ES=0.84) Acceleration: 6.6 ± 2.4% greater than control (P<0.01, ES=1.0)
Smith et al. (2014)	11 males, 11 females PA students 23 ± 5 years	Sled resisted sprint with 0, 10, 20 and 30% BM	1 set x 1 rep over 18.3 m	4 min	36.5 m	Sprint time: 1-2% (0.07-0.13 s) faster 40 m time compared to pre warm-up (p < 0.001, ES=0.33)
Whelan, O'Regan, and Harrison (2014)	12 PA males 22.5 ± 3.9 years, 1.77 ± 0.05 m, 74.0 ± 5.9 kg	Sled resisted sprint with 25-30% BM	1 set x 3 reps over 10 m	1 min 2 min 4 min 6 min 8 min 10 min	10 m	No significant effects
Simperingham et al. (2015)	1 AT male 29.2 years, 180.8 cm, 87.2 kg	DJ from 0.45 m with 5% BM LBWR	3 sets x 5 reps	5 min	40 m	Sprint time: 1% slower at 40 m
Simperingham et al. (2015)	1 AT male 29.2 years, 180.8 cm, 87.2 kg	40 m sprints with 1-5% BM LBWR	1 sets x 3 reps	5 min	40 m	Sprint time: 3.3% faster at 10 m, no change at 40 m
Simperingham et al. (2015)	1 AT male 29.2 years, 180.8 cm, 87.2 kg	20 m flying start sprints with 1% BM LBWR	1 sets x 3 reps	5 min	40 m	Sprint time: no change
Simperingham et al. (2015)	1 AT male 29.2 years, 180.8 cm, 87.2 kg	Dynamic warm-up exercises with 3% BM LBWR	1 x warm-up (10 min)	5 min	40 m	Sprint time: 3.8% faster at 10 m, 1.2% faster at 30 m, 1.5% faster at 40 m

Study	Subjects	Ballistic exercise intervention	Training volume	Rest time prior to testing	Sprint distance	Sprint performance outcomes
Turner et al. (2015)	23 AT males 22 ± 1 years, 1.82 ± 0.08 m, 82.4 ± 8.7	Alternate leg bounding	3 sets x 10 reps		20 m	Velocity:
				15 s		10 m and 20 m no significant effect
				2 min		10 m and 20 m no significant effect
				4 min		10 m velocity increased 1.8 ± 3.3% compared to control (P=0.047) 20 m velocity increased 1.4 ± 2.3% compared to control (P=0.007)
				8 min		10 m and 20 m no significant effect
				12 min		10 m and 20 m no significant effect
				16 min		10 m and 20 m no significant effect
Turner et al. (2015)	23 AT males 22 ± 1 years, 1.82 ± 0.08 m, 82.4 ± 8.7	Alternate leg bounding with 10% BM WV	3 sets x 10 reps		20 m	Velocity:
				15 s		10 m no significant effect 20 m slower 1.4 ± 2.5% than control (P=0.039)
				2 min		10 m and 20 m no significant effect
				4 min		10 m increased 2.1 ± 3.1% than control (P=0.009) 20 m increased 2.3 ± 2.6% than control (P<0.001)
				8 min		10 m increased 2.9 ± 3.6% than control (P=0.002) 20 m increased 2.6 ± 2.8% than control (P<0.001)
				12 min		10 m and 20 m no significant effect
				16 min		10 m and 20 m no significant effect
Dello et al. (2016)	26 AT males 15.4 ± 0.3 years, 1.69 ± 0.06 m, 61.4 ± 7.6 kg	DJ from 0.25 m 2 leg landing	3 sets x 10 reps		20 m	Sprint time:
				15 s		No significant effect
				4 min		No significant effect
				8 min		No significant effect
				16 min		No significant effect
				24 min		No significant effect
				30 min		2.1% (0.07 s) slower than control (P<0.05)

Study	Subjects	Ballistic exercise intervention	Training volume	Rest time prior to testing	Sprint distance	Sprint performance outcomes
Dello et al. (2016)	26 males AT 15.4 ± 0.3 years, 1.69 ± 0.06 m, 61.4 ± 7.6 kg	DJ from 0.25 m 1 leg landing	3 set x 5 reps	 15 s 4 min 8 min 16 min 24 min 30 min	20 m	Sprint time: No significant effect No significant effect No significant effect 2.1% (0.07 s) slower than control (P<0.05) 2.7% (0.09 s) slower than control (P<0.05) 2.4% (0.08 s) slower than control (P<0.05)
Kümmel et al. (2016)	International sprinters 2 males, 21 ± 2 years, 1.86 ± 0.14 m, 99 ± 19 kg 3 females, 23 ± 8 years, 1.81 ± 0.03 m, 79 ± 8 kg	2 leg repetitive bounds	1 set x 10 reps before each single sprint (4 sprints total)	10 s	30 m	No significant effects
Lockie et al. (2016)	3 females ST 23.0 ± 2.7 years; 1.61 ± 0.06 m; 56.4 ± 5.4 kg	SJ with 30% of 1RM back squat OR Alternate leg bounding	3 sets x 5 reps (SJ) or 10 reps (bounding)	15 s 2 min 4 min 8 min 12 min 16 min	20 m	Case study results indicated small increases and decreases in sprint performance of 1-4%, which were not clearly different to the control (walking) condition
Winwood et al. (2016)	22 males AT 22.4 ± 3.0 years, 1.78 ± 0.06 m, 87.6 ± 13.0 kg	Sled resisted sprint with 75% and 150% BM	1 set x 15 m (75% BM) and 1 set x 7.5 m (150% BM)	4 min 8 min 12 min	15 m	No significant effects for either load No significant effects for either load Sprint time: 0.8% (0.02 s) faster than control (P=0.036) with 75% BM
Van Den Tillaar et al. (2017)	30 males AT 21.2 ± 2.9 years, 1.75 ± 0.008 m, 69.8 ± 9.8 kg	Sled resisted sprint with 10% BM	7x 60 m (alternating unloaded and resisted sprints)	5 min	60 m	No significant effect on sprint times

Study	Subjects	Ballistic exercise intervention	Training volume	Rest time prior to testing	Sprint distance	Sprint performance outcomes
Van Den Tillaar and Von Heimburg (2017)	15 female AT 19.2 ± 1.2 years, 1.74 ± 0.04 m, 68.4 ± 9.1 kg	Assisted sprints with pulley system (40 kg) attached to participant waist	7x 20 m (alternating assisted then unloaded sprints)	5-6 min	20 m	No significant effect on sprint times
		Resisted sprints with pulley system (5 kg) attached to participant waist	7x 20 m (alternating resisted then unloaded sprints)	5-6 min	20 m	No significant effect on sprint times
Jarvis, Turner, Chavda, and Bishop (2017)	8 males PA 21.8 ± 0.8 years, 1.85 ± 0.05 m, 88.8 ± 15.7 kg	Sled resisted sprint with 50% BM	1 set x 1, 2, and 3 reps	4 min 8 min 12 min	15 m	No significant effect Sprint time: 2.8% (0.07 s) faster than control (P=0.025, ES: 0.46) for 3 rep No significant effect
Seitz et al. (2017)	20 males AT 18.4 ± 0.8 years, 1.80 ± 0.08 m, 80.4 ± 6.8 kg	Sled resisted sprint push with 75% and 125% BM	1 set x 15 m (75% BM) and 1 set x 9 m (125% BM)	15 s 4 min 8 min 12 min	20 m	Sprint time: no significant effects with 75% BM, slower 2.7%, (0.9 s, ES: 0.64, P<0.05) with 125% Sprint time: no significant effects with 75% BM, slower 2.1%, (0.7 s, ES: 0.53, P<0.05) with 125% Sprint time: 1.9% (0.6 s, ES: 0.42, P<0.05) faster with 75% BM, no significant effects with 125% BM Sprint time: 1.6% (0.5s, ES: 0.36, P<0.05) faster with 75% BM, no significant effects with 125% BM

Note. 1RM = one repetition maximum; reps = repetitions; AT = athletically trained; BM = body mass; CMJ = countermovement jump; DJ = drop jump; ES = effect size; LBWR = lower body wearable resistance; PA = physical active; SJ = squat jump; ST = strength trained; WV = weighted vest

Table 13. Sprint-running performance change following different rest interval periods after jumps and bounds (n=9).

Rest interval prior to testing	**Type of jumps**	**Changes in sprint-running performance**
≤ 15 s	DJ from 0.25 m 2 leg landing	No significant effect on sprint time (Dello et al., 2016)
	DJ from 0.25 m 1 leg landing	No significant effect on sprint time (Dello et al., 2016)
	Alternate leg bounding	No significant effect on velocity (Turner et al., 2015)
	Alternate leg bounding with 10% BM WV	No significant effect on velocity (Turner et al., 2015)
	2 leg repetitive bounds	No significant effect on sprint time ((Kümmel et al., 2016))
	SJ with 30% of 1RM back squat	Sprint times faster at 5 m 2.7% and 10m 1.2% (Lockie et al., 2016)
	Alternate leg bounding	No significant effect on sprint time (Lockie et al., 2016)
1 min	DJ from individual optimum heights	Sprint time: 5.0% (0.17 s) faster than control (P=0.001,ES=0.84) and 2.9% (0.10 s) faster than dynamic warm-up (P=0.001) (Byrne et al., 2014)
2 min	Alternate leg bounding	No significant effect on velocity (Turner et al., 2015)
	Alternate leg bounding with 10% BM WV	No significant effect on velocity (Turner et al., 2015)
	SJ with 30% of 1RM back squat	Sprint times faster at 10 m 1.2% and 20m 1.7% (Lockie et al., 2016)
	Alternate leg bounding	Sprint times faster at 5m 1% (Lockie et al., 2016)
4 min	Tuck jump	No significant effect on sprint time (Till & Cooke, 2009)
	DJ from 0.25 m 2 leg landing	No significant effect on sprint time (Dello et al., 2016)
	DJ from 0.25 m 1 leg landing	No significant effect on sprint time (Dello et al., 2016)
	Alternate leg bounding	Velocity: 10 m increased 1.8 ± 3.3% (P=0.047), 20 m increased 1.4 ± 2.3% (P=0.007) (Turner et al., 2015)
	Alternate leg bounding with 10% BM WV	Velocity: 10 m increased 2.1 ± 3.1% (P=0.009), 20 m increased 2.3 ± 2.6% (P<0.001) (Turner et al., 2015)
	SJ with 30% of 1RM back squat	Sprint times faster at 5 m 3.7% and 10 m 3.8% and 20m 2.2% (Lockie et al., 2016)
	Alternate leg bounding	Sprint times faster at 5m 2.8% and 10m 1.3% (Lockie et al., 2016)
4-6 min	CMJ with 30% of 1RM back squat	No significant effect on sprint time (Mcbride et al., 2005)
5 min	DJ from 0.75 m	No significant effect on sprint time (Bomfim Lima et al., 2011)
	DJ from 0.45 m with 5% BM LBWR	No significant effect on sprint time (Simperingham et al., 2015)
8 min	DJ from 0.25 m 2 leg landing	No significant effect on sprint time (Dello et al., 2016)
	DJ from 0.25 m 1 leg landing	No significant effect on sprint time (Dello et al., 2016)
	Alternate leg bounding	No significant effect on velocity (Turner et al., 2015)
	Alternate leg bounding with 10% BM WV	Velocity: 10 m increased 2.9 ± 3.6% (P=0.002), 20 m increased 2.6 ± 2.8% (P<0.001) (Turner et al., 2015)
	SJ with 30% of 1RM back squat	Sprint times faster at 5 m 1-3.4% and 10m 1% (Lockie et al., 2016)
	Alternate leg bounding	Sprint times faster at 5m 1.8% and 10m 1% (Lockie et al., 2016)
10 min	DJ from 0.75 m	Sprint time faster 2.4% (0.16 s) than control (P<0.05, ES=0.66) (Bomfim Lima et al., 2011)
12 min	Dynamic warm-up with 2% BM WV	No significant effect on sprint time (Faigenbaum et al., 2006)
	Dynamic warm-up with 6% BM WV	No significant effect on sprint time (Faigenbaum et al., 2006)

Rest interval prior to testing	Type of jumps	Changes in sprint-running performance
	Alternate leg bounding	No significant effect on velocity (Turner et al., 2015)
	Alternate leg bounding with 10% BM WV	No significant effect on velocity (Turner et al., 2015)
	SJ with 30% of 1RM back squat	Sprint times faster at 5m 3.5% and 10 m 2.1% (Lockie et al., 2016)
	Alternate leg bounding	Sprint times faster at 5m 2.1% and 10m 1.8% (Lockie et al., 2016)
15 min	DJ from 0.75 m	Sprint time faster 2.7% (0.17 s) than control ($P<0.05$, ES=0.69) (Bomfim Lima et al., 2011)
16 min	DJ from 0.25 m 2 leg landing	No significant effect on sprint time (Dello et al., 2016)
	DJ from 0.25 m 1 leg landing	Sprint time slower 2.1% (0.07 s) than control ($P<0.05$) (Dello et al., 2016)
	Alternate leg bounding	No significant effect on velocity (Turner et al., 2015)
	Alternate leg bounding with 10% BM WV	No significant effect on velocity (Turner et al., 2015)
	SJ with 30% of 1RM back squat	No changes (Lockie et al., 2016)
	Alternate leg bounding	Sprint time faster at 5m 1.7% and 10m 1.8% (Lockie et al., 2016)
24 min	DJ from 0.25 m 2 leg landing	No significant effect on sprint time (Dello et al., 2016)
	DJ from 0.25 m 1 leg landing	Sprint time slower 2.7% (0.09 s) than control ($P<0.05$) (Dello et al., 2016)
30 min	DJ from 0.25 m 2 leg landing	Sprint time slower 2.1% (0.07 s) than control ($P<0.05$) (Dello et al., 2016)
	DJ from 0.25 m 1 leg landing	Sprint time slower 2.4% (0.08 s) than control ($P<0.05$) (Dello et al., 2016)

Note. 1RM = one repetition maximum; BM = body mass; CMJ = countermovement jump; DJ = drop jump; ES = effect size; LBWR = lower body wearable resistance; SJ = squat jump; WV = weighted vest

Table 14. Sprint-running performance change following different rest interval periods after resisted sprints (n=8).

Rest interval prior to testing	**Type of resisted sprint**	**Changes in sprint-running performance**
15 s	20 m sled resistance 75% BM	No significant effect on sprint time (Seitz et al., 2017)
	20 m sled resistance 125% BM	Sprint time slower 2.7% (0.9 s, ES: 0.64, $P<0.05$) (Seitz et al., 2017)
1 min	10 m sled resistance 25-30% BM	No significant effect on sprint time (Whelan et al., 2014)
2 min	10 m sled resistance 25-30% BM	No significant effect on sprint time (Whelan et al., 2014)
4 min	10 m sled resistance 25-30% BM	No significant effect on sprint time (Whelan et al., 2014)
	15m sled resistance 75% BM	No significant effect on sprint time (Winwood et al., 2016)
	7.5 m sled resistance 150% BM	No significant effect on sprint time (Winwood et al., 2016)
	10 m sled resistance 10, 20 and 30% BM	No significant effects for any load (Smith et al., 2014)
	15 m sled resistance 50% BM	No significant effect on sprint time (Jarvis et al., 2017)
	20 m sled resistance 75% BM	No significant effect on sprint time (Seitz et al., 2017)
	20 m sled resistance 125% BM	Sprint time slower 2.1% (0.7 s, ES: 0.53, $P<0.05$) (Seitz et al., 2017)
5 min	40 m sprints with 1-5% BM LBWR	Sprint time faster 3.3% at 10 m, no change at 40 m (Simperingham et al., 2015)
	20 m flying start sprints with 1% BM LBWR	No significant effect on sprint time (Simperingham et al., 2015)
	60 m sled resisted sprints with 10% BM	No significant effect on sprint time (Van Den Tillaar et al., 2017)
	20 m pulley resisted sprints with 5 kg	No significant effect on sprint time (Van Den Tillaar & Von Heimburg, 2017)
	20 m pulley assisted sprints with 40 kg	No significant effect on sprint time (Van Den Tillaar & Von Heimburg, 2017)
6 min	10 m sled resistance 25-30% BM	No significant effect on sprint time (Whelan et al., 2014)
8 min	10 m sled resistance 25-30% BM	No significant effect on sprint time (Whelan et al., 2014)
	15m sled resistance 75% BM	No significant effect on sprint time (Winwood et al., 2016)
	7.5 m sled resistance 150% BM	No significant effect on sprint time (Winwood et al., 2016)
	15 m sled resistance 50% BM	Sprint time faster 2.8% (0.07 s) than control ($P=0.025$, ES: 0.46) for 3 rep (Jarvis et al., 2017)
	20 m sled resistance 75% BM	Sprint time faster 1.9% (0.6 s, ES: 0.42, $P<0.05$) (Seitz et al., 2017)
	20 m sled resistance 125% BM	No significant effect on sprint time (Seitz et al., 2017)
10 min	10 m sled resistance 25-30% BM	No significant effect on sprint time (Whelan et al., 2014)
12 min	15m sled resistance 75% BM	Sprint time faster 3.1 ± 1.1% (0.02 s) than control ($P=0.036$) with 75% BM load (Winwood et al., 2016)
	7.5 m sled resistance 150% BM	No significant effect on sprint time (Winwood et al., 2016)
	20 m sled resistance 75% BM	Sprint time faster 1.6% (0.5 s, ES: 0.36, $P<0.05$) (Seitz et al., 2017)
	15 m sled resistance 50% BM	No significant effect on sprint time (Jarvis et al., 2017)
	20 m sled resistance 125% BM	No significant effect on sprint time (Seitz et al., 2017)

Note. BM = body mass; ES = effect size; LBWR = lower body wearable resistance

Table 15. Sprint-running performance change following different rest interval periods after power clean (n=2).

Rest interval prior to testing	Type of resisted sprint	Changes in sprint-running performance
1 min	1 set x 3 reps at 90% of 1RM	No significant effect on sprint time (Guggenheimer et al., 2009)
7 min	1 set x 3 reps at 90% of 1RM	Sprint time: 3.1 ± 1.1% (0.10 s) faster than control ($P<0.01$, ES=0.92), velocity: 3.2 ± 1.2% greater than control ($P<0.01$, ES=0.84), acceleration: 6.6 ± 2.4% greater than control ($P<0.01$, ES=1.0) (Seitz et al., 2014)

Note. 1RM = one repetition maximum; ES = effect size

Muscle temperature directly influences power performance (Kilduff, West, Williams, & Cook, 2013; Sargeant, 1987), however muscle temperature changes have not been directly addressed in the research focusing on ballistic exercise and APE of sprint performance. At relatively slow contraction velocities peak power output tends to increase by about 2% per 1 °C increase in muscle temperature, but the increase in peak power is approximately 10% per 1 °C increase in muscle temperature at relatively fast contraction velocities (Sargeant, 1987). Understanding the impact of muscle temperature is particularly important in order to optimise APE interventions, but also controlling for muscle temperature changes is crucial in future APE and PAP research (Kilduff et al., 2013; Sargeant, 1987).

Turner et al. (2015) concluded that faster individuals appeared to benefit more from a plyometric intervention, but also experienced more fatigue. Collecting a proxy measure for muscle fibre type composition could assist in determining if this difference is related to the proportion of fast twitch muscle fibres in an individual and therefore fatigability. Smith et al. (2014) tested participants on an inertial load cycle test, which in addition to power output, provided optimal cadence (i.e. pedalling rate at peak power) results that are known to be well correlated with muscle fibre type composition of the thighs (Hautier, Linossier, Belli, Lacour, & Arsac, 1996). It was concluded that muscle fibre type did not influence the APE results, however the optimal cadence results were not reported.

Limitations

Due to the diverse ballistic exercise options available and the complex interaction between the characteristics of the conditioning stimulus and the characteristics of the individual, it is difficult to make precise practical recommendations based on the current body of research in the area. The need for individual experimentation appears to be unavoidable. A limitation of the available research is that there has been very little focus on the maximum velocity sprint phase. Even when sprints of > 20 m were examined, maximum velocity phase split times were rarely reported separately. For example, a 40 m sprint time provides a quantification of the combined acceleration phase and maximum velocity phase, whereas the time to cover the 10 m sprint section between 30 m and 40 m gives a representation of maximum velocity without the early acceleration component. Given the clear differences between the acceleration phase and the maximum velocity phase, it would seem prudent for researchers to report the relevant outcome variables separately when possible.

Other limitations of the papers included in the current review were that the participants were often athletically trained males, meaning that applying the results to females or to an elite sporting population should be done with caution. Sample sizes were also generally quite small, particularly when a well-trained population was assessed (e.g. Kümmel et al., 2016).

Future Research

Future research in this area should acknowledge the consistent conclusion that there are individual differences in the response to a ballistic exercise conditioning stimulus. Data should be analysed using individually optimised rest period lengths (Jarvis et al., 2017) to determine the efficacy of combinations of ballistic exercise and acceleration phase and maximum velocity phase sprinting. Assessing a broader range of the factors that are known to potentially influence APE effects (e.g. training status, strength, muscle/body temperature, limb stiffness and muscle fibre type composition) will also improve the understanding in this area and therefore the training recommendations that can be made.

Recent advances in WR technology have greatly increased the range of options available for adding external load specifically to ballistic movements (Macadam, Cronin, et al., 2017; Macadam et al., 2018). A thorough understanding of the relationship between ballistic exercise and sprint performance will enable WR and other loading options to be optimally incorporated into speed programs.

Conclusions

A significant APE (typically 1-5%) of sprint performance can occur between 15 seconds and 16 minutes after loaded and unloaded BE. Both fatigue and enhancement effects tended to be greater and longer lasting after higher volume ballistic exercise and after relatively more intense ballistic exercise options such as unilateral jumps and loaded BE. Based on the limited number of studies in the area to date, the following APE optimal rest period guidelines were proposed: approximately 1 minute after unloaded jumps with < 10 jump contacts; 4-16 minutes after unloaded and loaded jumps with ≥ 10 jump contacts; 8-12 minutes after heavy (50-75% BM) resisted sprints; and approximately 7 minutes after heavy power cleans. A longer rest period may tend to be optimal when the APE target is the maximum velocity phase rather than the acceleration phase. Further research is required using WR to increase the intensity of ballistic exercise pre-conditioning stimuli, including loaded dynamic warm-ups. Research focus on the maximum velocity phase as well as on the range of individual characteristics that may influence APE effects will strengthen the understanding of ballistic exercise and the APE of sprinting.

SECTION 3

ACUTE CHANGES IN SPRINT-RUNNING PERFORMANCE WITH WEARABLE RESISTANCE TRAINING

CHAPTER 7

CHANGES IN SPRINT KINEMATICS AND KINETICS WITH UPPER-BODY AND LOWER-BODY LOADING USING EXOGEN EXOSKELETONS

This paper comprises the following paper published in *Journal of Australian Strength and Conditioning*:

Simperingham, K. D. & Cronin, J. B. (2014). Changes in sprint kinematics and kinetics with upper body loading and lower body loading using Exogen exoskeletons: a pilot study. *Journal of Australian Strength and Conditioning*, 22(5), 69-72.

Prelude

The two related areas of WR training and the effect of loaded and unloaded ballistic exercise on subsequent sprint performance were reviewed in Section 2. The main findings of Chapter 6 were that sprint performance can be significantly improved between 15 seconds and 16 minutes after ballistic exercise and that fatigue and enhancement effects tended to be greater and longer lasting after higher volume and more intense ballistic exercise options. Assessing the APE effects of loaded warm-ups using WR is an area deserving more research attention, so will be the focus of the cross-sectional study in Chapter 10. Section 3 contains three other cross-sectional chapters, each addressing gaps in the literature identified in the WR narrative review (Chapter 5): the kinematic and kinetic differences in sprint performance with upper body and lower body WR (Chapter 7); and the changes in sprint biomechanics with lower body WR during the acceleration phase (Chapter 8) and the maximum velocity phase (Chapter 9). No studies to date have quantified the effects of the same magnitude of WR attached to the upper body compared to the lower body during sprinting. A brief subjective questionnaire was also used in Chapter 7 to explore participant perceptions about using WR during sprinting for the first time.

Introduction

Key determinants of sprint performance include the magnitude and direction of the GRF exerted and the duration of each ground CT (Hay, 1993; Hunter et al., 2005; Morin et al., 2011). It is therefore important to understand how these kinematic and kinetic variables are acutely modified by different training techniques. One such technique is resisted sprint training where tools such as weighted vests may be used with the aim of acutely or chronically improving unloaded sprint performance (Clark et al., 2010; Cronin & Hansen, 2006). With regards to acute loading, resisted sprint training is often followed by a contrast series of unloaded sprints with the goal of achieving an acute enhancement in unloaded sprint performance due to the acute pre-conditioning effect of the loaded sprints, however this technique has not been empirically supported (Whelan et al., 2014). Acute changes during sprints with a heavy vest [~11-22% of body mass (BM)] included significantly decreased SL, FT and sprint velocities, significantly increased CT, and reduced or unchanged SF (Cronin et al., 2008; Cross et al., 2014). Smaller relative loads of up to 1.8 kg per leg (total of approximately 4.8% of BM) attached just above the ankle joint also resulted in a significant acute decrease in sprint velocity, which was due mainly to a reduction in stride frequency (Ropret et al., 1998). Based on analysis of upper body vest loading during sprint-running on a NMT it was reported that loads well in excess of 10% of BM are required to elicit a significant acute increase in F_v compared to baseline unloaded sprinting (Cross et al., 2014). Similar kinetic analysis of maximal-effort sprinting with added external lower body loading, and a direct comparison of both the kinematic and kinetic effects of upper compared to lower body loading has not been reported in the literature.

The Lila™ Exogen™ compression-based exoskeleton suit (Sportboleh Sdh Bhd, Malaysia) (Figure 10) is a new product that enables numerous loading configurations (e.g. anterior vs posterior, proximal vs distal, and upper vs lower body) for resisted sprint training. The aim of this study was to determine the changes in kinematic and kinetic variables during short sprints on a NMT with added lower body loading compared to added upper body loading and unloaded sprinting using the exoskeleton. A secondary aim was to determine if unloaded sprint performance was improved through a potentiating effect following the completion of a series of sprints with added loads. The sprint phases of acceleration and maximum velocity are distinctly different (Mann, 2011; Mero, Komi, & Gregor, 1992), so will be analysed separately where applicable in this study.

Figure 10. Lila™ Exogen™ exoskeleton suit. Upper body loading condition (UB5%) from anterior (**a**) and posterior (**b**) view. Lower body loading condition (LB5%) from anterior (**c**) and posterior (**d**) view.

Methods

Eight athletic males (29.2 ± 3.8 years, 81.8 ± 9.7 kg, 177.1 ± 7.5 cm) with at least two years' experience playing sprint-based team sports, completed a 20-minute standardized familiarisation and warm-up protocol followed by four sets of two maximal effort 6 s sprints on a Woodway Force 3.0 (Eugene, OR, USA) NMT ergometer. Procedures for testing on the treadmill and post-processing of the treadmill-derived data was consistent with procedures previously reported by (Brown, Brughelli, & Cross, 2016). Passive rest of 3 - 5 minutes between test trials and 5 - 6 minutes between sets was used throughout each testing session. Participants wore Lila™ Exogen™ exoskeleton suits (Figure 10) during the entire testing session. An additional load of 5% of BM was attached to the suits prior to Set 2 and removed again after the completion of Set 3. In a randomised order the additional load was attached to the upper body (UB5%) for one set and to the lower body (LB5%) for the other set. The upper body loads were positioned evenly on the anterior and posterior surfaces of the vest. The lower body loads were attached in an even manner to the anterior and posterior surfaces of the shorts, with 0.4-0.8 kg also attached evenly to the anterior and posterior aspect of each lower leg sleeve. Set 1 and 4 sprints were the unloaded, reference conditions (UL-PRE and UL-POST respectively).

A “blocked” sprint start position was used, involving the experimenter manually stopping any belt movement prior to the sprint start by placing a foot on the back of the belt surface, thus allowing the subject to assume a typical standing split stance start position with their body leaning forward. Subjects wore a harness around their waists with a rigid tether connecting the harness to a horizontal load cell on a vertical strut directly behind the treadmill belt surface. The vertical position of the load cell was adjusted to ensure that the tether remained parallel to the treadmill surface during each trial. Methods consistent with those previously reported (Brughelli et al., 2011; Cross et al., 2014) were used to calculate instantaneous horizontal velocity (v); as well as peak F_v, mean F_v ($F_v$mean), peak F_h and peak horizontal power output (PP) during each foot contact; and also average CT, FT, SF and SL during each sprinting phase. Split times for distances between 2 m and 25 m were also determined. Data collection occurred through the hardwired NMT system interface (XPV7 PCB, Fitness Technology, Adelaide, Australia) at a sampling frequency of 200 Hz. Participants provided qualitative feedback on the exoskeleton suit and the perceived impact on sprint performance by completing a written questionnaire at the end of the testing session. A custom-built LabVIEW software program (LabVIEW, National Instruments, Texas, USA) was used for post-processing of the data and enabled the selection of time windows relating to the period of each foot contact. Three distinct phases of the sprint were selected and compared in the analysis: the first two steps, representing the start phase; the next ten steps (i.e. steps 3-12), representing the acceleration phase; and the subsequent ten steps (i.e. steps 13-22), representing the maximum velocity phase. Kinematic and kinetic variables were averaged over all foot contacts (i.e. two or ten steps) during each of the three sprinting phases. CT, FT, SF and SL were not calculated during the SP as most subjects did not achieve a period of flight during this phase. In addition to absolute values, F_v and $F_v$mean variables were also analysed relative to BM (UL-PRE and UL-POST) or relative to BM plus the additional external load (UB5% and LB5%). Output variables were averaged across the two trial repetitions in each set. Statistical analysis was completed using a generalised linear mixed model with between-subject variance included as a random effect. Bonferroni-adjusted post-hoc contrasts were used to identify significant differences among the loading conditions (UL-PRE, UB5%, LB5%, UL-POST) for each kinematic and kinetic variable and during each of the three sprinting phases (i.e. start, acceleration and maximum velocity phases). Statistical significance was set at $p < 0.05$.

Results

Seven out of eight participants (87.5%) perceived enhanced performance during the UL-POST condition compared to UL-PRE, however the only evidence of a potentiating effect was a significant 1.3% increase in F_v compared to UL-PRE during the maximum velocity phase. There were no other significant differences between UL-PRE and UL-POST. Kinematic and kinetic differences during the start phase of the sprints were also largely absent. Further reporting of UL-POST results and all start phase results are therefore excluded from the following analysis.

Kinematic Variables

There was only a < 2% increase in the peak velocity achieved in the maximum velocity phase compared to acceleration phase, confirming that the majority of the change in speed had occurred prior to the maximum velocity phase.

UB5% vs UL-PRE (Control): There was no significant effect of upper body loading on peak velocity, SF, SL or the time to cover any distance between 2 m and 25 m compared to the unloaded control condition (UL-PRE) (Table 16). There was, however, a significant increase in CT during the acceleration phase (3.8%) and the maximum velocity phase (4.7%) as well as a significant decrease in FT during the acceleration phase (-15%) with UB5% compared to UL-PRE.

LB5% vs UL-PRE (Control): There was no significant effect of lower body loading on the time to cover 2 m to 10 m, however the split times between 15 m and 25 m and the peak velocities achieved in the acceleration phase and the maximum velocity phase were significantly slower by -2.0 to -5.3% compared to UL-PRE. FT and SL were not significantly changed with LB5% compared to UL-PRE, however the lower body loading did result in a significant increase in CT during the acceleration phase (4.3%) and the maximum velocity phase (4.7%) and a significant decrease in SF during both the acceleration phase (-3.6%) and the maximum velocity phase (-3.5%) compared to UL-PRE.

LB5% vs UB5%: The time to cover distances above 10 m and the peak velocities achieved during the acceleration phase and the maximum velocity phase were significantly slower by -2.3 to -4.2% with LB5% compared to UB5%. The only other significant difference in the kinematic variables was a -2.9% reduction in SF during acceleration phase with LB5% compared to UB5%.

Kinetic Variables

*UB5% vs UL-PRE (*Control): There was no significant change in absolute kinetic values, but there was a significant reduction in relative values for F_v (-5.4 to -6.4%) and $F_v$mean (-3.8 to -4.0%) during the acceleration phase and the maximum velocity phase with UB5% compared to UL-PRE (Table 17).

LB5% vs UL-PRE (Control): Lower body loading resulted in a significant increase in F_v during the acceleration phase (4.0%) and the maximum velocity phase (4.6%), and a significant increase in $F_v$mean during the acceleration phase (4.0%) compared to UL-PRE. All other absolute and relative kinetic values were not significantly different compared to the unloaded control condition.

LB5% vs UB5%: Absolute values for F_v (acceleration phase and maximum velocity phase) and $F_v$mean (acceleration phase) and relative values for F_v (acceleration phase and maximum velocity phase) and $F_v$mean (acceleration phase and maximum velocity phase) were significantly greater by 2.3-5.8% with LB5% compared to UB5%. There was no significant difference in the F_h and PP results between the upper body loading and lower body loading conditions.

Table 16. Split times (mean ± SD) achieved between 2 m and 25 m, and additional kinematic outputs during the acceleration phase and maximum velocity phase under the unloaded (UL-PRE), upper body (UB5%) and lower body (LB5%) loading conditions.

	UL-PRE	**UB5%**	**LB5%**
2 m (s)	1.12 ± 0.11	1.11 ± 0.10	1.10 ± 0.12
5 m (s)	1.83 ± 0.16	1.82 ± 0.15	1.83 ± 0.17
10 m (s)	2.83 ± 0.24	2.81 ± 0.21	2.86 ± 0.23
15 m (s)	3.79 ± 0.31	3.78 ± 0.28	3.87 ± 0.29 [a,b]
20 m (s)	4.76 ± 0.38	4.76 ± 0.34	4.88 ± 0.35 [a,b]
25 m (s)	5.73 ± 0.46	5.75 ± 0.41	5.92 ± 0.42 [a,b]
10-20 m (s)	1.92 ± 0.16	1.94 ± 0.14	2.02 ± 0.14 [a,b]
Peak Velocity (m/s)			
Acceleration phase	5.24 ± 0.48	5.22 ± 0.41	5.05 ± 0.36 [a,b]
Max. velocity phase	5.33 ± 0.43	5.27 ± 0.39	5.07 ± 0.35 [a,b]
CT (ms)			
Acceleration phase	184 ± 12	191 ± 12 [a]	192 ± 12 [a]
Max. velocity phase	170 ± 11	178 ± 16 [a]	178 ± 15 [a]
FT (ms)			
Acceleration phase	40 ± 15	34 ± 12 [a]	40 ± 15 [b]
Max. velocity phase	51 ± 13	47 ± 14	51 ± 14 [b]
SF (Hz)			
Acceleration phase	4.49 ± 0.27	4.46 ± 0.25	4.33 ± 0.23 [a,b]
Max. velocity phase	4.53 ± 0.25	4.36 ± 0.30	4.37 ± 0.23 [a]
SL (m)			
Acceleration phase	1.17 ± 0.14	1.17 ± 0.13	1.24 ± 0.16
Max. velocity phase	1.18 ± 0.14	1.21 ± 0.12	1.16 ± 0.12

Note. SD = standard deviation; CT = contact time; FT = flight time; SF. = step frequency; SL = step length

a Significantly different from UL-PRE; b Significantly different from UB5%

Table 17. Kinetic outputs (mean ± SD) during the acceleration phase and the maximum velocity phase under the unloaded (UL-PRE), upper body (UB5%) and lower body (LB5%) loading conditions.

	UL-PRE	**UB5%**	**LB5%**
F_v (N)			
Acceleration phase	1768 ± 321	1738 ± 297	1839 ± 306 [a,b]
Max. velocity phase	1916 ± 287	1905 ± 299	2004 ± 327 [a,b]
$F_v$mean (N)			
Acceleration phase	987 ± 169	996 ± 160	1027 ± 169 [a,b]
Max. velocity phase	1067 ± 163	1080 ± 162	1111 ± 175
F_h (N)			
Acceleration phase	321 ± 29	318 ± 29	323 ± 31
Max. velocity phase	268 ± 36	261 ± 24	273 ± 36
PP (W)			
Acceleration phase	1449 ± 296	1430 ± 267	1437 ± 258
Max. velocity phase	1422 ± 275	1362 ± 199	1378 ± 253
Rel. F_v (N/kg)			
Acceleration phase	2.20 ± 0.26	2.06 ± 0.22 [a]	2.18 ± 0.23 [b]
Max. velocity phase	2.39 ± 0.23	2.26 ± 0.26 [a]	2.37 ± 0.25 [b]
Rel. $F_v$mean (N/kg)			
Acceleration phase	1.23 ± 0.10	1.18 ± 0.08 [a]	1.22 ± 0.10 [b]
Max. velocity phase	1.33 ± 0.10	1.28 ± 0.10 [a]	1.31 ± 0.10 [b]

Note. SD = standard deviation; F_v = peak vertical ground reaction force; $F_v$mean = mean vertical ground reaction force; F_h = peak horizontal ground reaction force; PP = peak horizontal power output; Rel. F_v = relative peak vertical ground reaction force; Rel. $F_v$mean = relative mean vertical ground reaction force

[a] Significantly different from UL-PRE; [b] Significantly different from UB5%

Discussion

An additional external load of 5% of BM attached to the upper body did not change short sprint split times up to 25 m, however the same additional load attached to the lower body resulted in a significant increase in time to cover distances greater than 10 m. The decrement in sprint performance due to lower body loading tended to become more pronounced as the sprint distance increased. While there were similar effects on CT and SL for both loading conditions, the external lower body loading increased the rotational inertia of the lower body with a likely concomitant decrease in angular velocity of the lower limbs and hence affected swing mechanics by increasing CT. Upper body loading did not affect CT, but resulted in a significant decrease in FT (-15%), which is likely explained by the pure vertical loading directed through the centre of mass.

Previously it was reported that upper body loading as high as 18 kg is required to achieve an increase in F_v during maximal sprinting (Cross et al., 2014). The absence of an increase in F_v with the relatively light upper body loading in the present study is consistent with this finding, however the evidence of a reduction in relative F_v is a novel finding that is in stark contrast to the increased absolute F_v with lower body loading. It would seem that when force is ratio scaled in some manner that the influence of external mass on the kinetics of the system (body mass plus external mass) is different to when expressed as an absolute load. Practitioners should be aware of this differential effect when interpreting results and applying findings. Cronin and Hansen (2006) theorised that longitudinal training with vest loading may result in increased eccentric strength and muscle stiffness, however the current results indicate that lower body loading provides a more effective vertical training stimulus at a load of 5% of BM.

Although almost all participants (87.5%) in the current study perceived enhanced performance in the final unloaded set of sprints, no significant change in sprint performance was found. This is consistent with previous research (Whelan et al., 2014), however contrasts with reports of enhanced sprint performance following heavy squats (Bevan et al., 2010). Further investigation is required to determine if a potentiating effect is also absent with altered loading configurations, magnitudes and sprint volumes. A potential limitation of the current study is that all sprint analysis took place on a NMT, so further testing should also assess whether the changes in kinetic and kinematic variables measured on the NMT are consistent with the changes that occur during over-ground resisted sprinting.

Practical Applications

The use of upper and lower body loading can have differential effects on the kinematics and kinetics of sprinting. External lower body loading with 5% of BM can be used to acutely increase F_v by up to 5% during the acceleration and maximum velocity sprint phases, while altering sprint kinematics (peak velocity, CT and SF) by less than 5%. External upper body loading with 5% of BM does not affect sprinting speed, but reduces FT by up to 15% and consequently results in decreased relative F_v outputs by up to 6%. A series of resisted sprints with Exogen™ exoskeleton suits may be an effective pre-conditioning stimulus to induce a perception of potentiated unloaded sprint performance, however objective evidence of enhanced sprint performance in this study is not apparent.

CHAPTER 8

CHANGES IN ACCELERATION PHASE BIOMECHANICS DURING OVER-GROUND AND TREADMILL SPRINTING WITH LOWER BODY WEARABLE RESISTANCE

This paper comprises the following paper submitted to *Sports Biomechanics*:

Simperingham, K. D., Cronin, J. B., Ross, A., Brown, S. R., Macadam, P. & Pearson, S. (2019). Changes in acceleration phase biomechanics during over-ground and treadmill sprinting with lower body wearable resistance. *Sports Biomechanics, [In review]*.

Prelude

The main findings of the previous chapter were summarised in a short video clip (https://www.youtube.com/watch?v=S3cUWj_cKv4) to assist in disseminating the results and practical applications. Sprinting speed was not significantly changed with upper body WR (5% BM), but relative F_v was significantly decreased (-4 to -6%). The equivalent load attached to the lower body resulted in a significant decrease in sprinting speed after the initial 10 m, but relative F_v was not significantly affected compared to unloaded sprinting. The combination of the specific overload and maintained vertical stimulus with lower body WR indicates that there may be relative advantages to this form of speed training. The results of the previous chapter were all collected during treadmill sprinting, however there are known differences between treadmill and over-ground sprinting. The aim of the following two chapters therefore was to quantify the changes in sprint performance and sprint biomechanics during over-ground sprinting. Chapter 8 involved a focus on the acceleration phase, and Chapter 9 a focus on the maximum velocity phase. As identified in the WR narrative review (Chapter 5), little is known about the effect of moderate and heavy WR during sprinting, so sprinting with two different WR loads (3% BM and 5% BM) was compared to unloaded sprinting. A subset of the data included in Chapter 8 was presented at *the 34th International Conference of Biomechanics in Sport* (Tsukuba, Japan), and the abstract is included in Appendix L.

Introduction

Optimised sprint-running acceleration performance is highly valued in many sports. Improvements in acceleration performance may be achieved through improved physiological capabilities (e.g. increased force production or movement velocity capabilities of the limbs) (Lockie et al., 2014; Lockie et al., 2012) or improved technical capabilities (e.g. more horizontally oriented GRF outputs or altered kinematic step characteristic) (Kugler & Janshen, 2010; Mann, 2011; Rabita et al., 2015). General methods of training (e.g. resistance training) can assist in improving sprint acceleration performance (Seitz et al., 2014), however more specific training techniques (e.g. plyometrics, sprinting and resisted/assisted sprinting) could be more effective for individuals with a higher training age (Brearley & Bishop, 2019; Dylan G et al., 2019; Macadam, Cronin, et al., 2017; Rumpf et al., 2016).

Resisted sprint training options include hills, parachutes, sleds and weighted garments. Recent advances in WR technology have enabled a greater degree of individualisation of load position, orientation and magnitude during sports training (Macadam, Cronin, et al., 2017). Instead of vest loading, WR loading of 5% BM or less attached to the lower body appears to be advantageous for sprint acceleration training (Simperingham & Cronin, 2014; Simperingham et al., 2015). Advantages may include the lower body loading being a more effective vertical training stimulus and/or the acute enhancement of sprint performance during unloaded sprinting several minutes after loaded sprints or a loaded dynamic speed warm-up (Simperingham & Cronin, 2014; Simperingham et al., 2015). However, a detailed understanding of the changes in sprint biomechanics with lower body WR is necessary to prescribe optimal sprint training interventions.

Ropret et al. (1998) reported a significant decrease in velocity and SF during the acceleration and maximum velocity sprint phases with foot loading as low as 0.6% BM. When the added load (2 to 3% BM) was spread over the thighs and shanks, researchers reported longer acceleration phase CT and lower SF, while sprint times were significantly slower after the initial 10 m (Bennett et al., 2009; Macadam, Simperingham, & Cronin, 2017). Treadmill sprinting with 5% BM attached to the lower body also resulted in a significant reduction in SF, reduced velocity after the initial 10 m, and increased ground CT and F_v (Simperingham & Cronin, 2014). Therefore, while relatively light lower body WR appears to overload some general performance descriptors of short sprints, no authors to date have reported on the effects of lower body WR with loads greater than 3% BM during over-ground sprinting or with loads less than 5% BM during treadmill sprinting.

The aim of this study was to quantify the kinematic and horizontal kinetic changes that occur during the acceleration phase of over-ground sprinting with 3 to 5% BM added lower body WR. A secondary aim was to quantify both the horizontal and vertical kinetic changes during treadmill sprinting under the same loaded conditions. It was hypothesised that over-ground results would replicate earlier treadmill sprint results with no significant change in sprint times over the initial 10 m even with loading up to 5% BM, but with significantly increased ground CT. It was further hypothesised that there would be no change in horizontal or vertical GRF or horizontal power. The purpose of the study was to achieve an improved understanding of how lower body WR acutely impacts sprint biomechanics, and therefore inform recommendations for the use of WR for short sprint acceleration training.

Methods

Participants

Fifteen male rugby union athletes (19.0 ± 0.5 years; 181.2 ± 7.3 cm; 91.0 ± 17.4 kg) volunteered for this study. All participants completed the over-ground sprint procedures. On a separate day, a subset of ten of the athletes (18.9 ± 0.4 years; 182.2 ± 6.5 cm; 96.6 ± 18.5 kg) also completed the non-motorised treadmill sprints. Participants were requested to not complete any high intensity training in the 24 hours prior to testing sessions and to present to the testing session well hydrated and having not eaten at least 90 minutes prior to the start of testing. Participants had no previous experience sprinting with lower body WR. Approval for the study was obtained from the institutional research ethics committee and participants provided written informed consent prior to participating in the study.

Procedures

Participants completed three sets of two 30 m sprints on an indoor running track and on a separate day completed three sets of two 30 m sprints on a Woodway Force 3.0 (Eugene, OR, USA) NMT. Procedures for testing on the treadmill and post-processing of the treadmill-derived data was consistent with procedures previously reported by (Brown, Brughelli, & Cross, 2016). Three loading conditions were compared: unloaded (0% BM added weight [AW]); moderate lower body loading (3% BM); and, heavy lower body loading (5% BM). The WR was attached with Velcro to Lila™ Exogen™ compression-based pants and calf sleeves (Sportboleh Sdh Bhd, Malaysia), with the load evenly distributed between the anterior and posterior aspects of the thigh and shank (respectively 2/3 and 1/3 of the total added weight) (Figure 11). Loading conditions were presented in a randomised order with five minutes of passive recovery between sprint repetitions and between sets.

Figure 11. Exogen compression-based pants and calf sleeves with added weight attached.

The initial 20 m of the over-ground and treadmill sprints were analysed as a representation of the acceleration sprint phase. Prior to the warm-up participants put on the Exogen™ pants and calf sleeves and wore them throughout the testing session. Height and body mass were recorded without shoes. A 20-minute standardised warm-up was completed on an indoor track (including jogging, sprint drills, dynamic stretching and build-up sprints of increasing intensity up to maximal effort). Prior to the treadmill sprints, participants performed the same standardised over-ground warm-up, but also completed an additional treadmill-specific warm-up on the non-motorised treadmill involving: a 30 s constant pace jog, finishing with one acceleration run up to approximately 75% effort; two 6 s sprints at 75-80% effort from a stationary start; two 3 s sprints at greater than 90% effort from a stationary start. After the warm-up there was a period of five minutes of passive rest to ensure full recovery. A “blocked” sprint start position was used, involving the experimenter manually stopping any belt movement prior to the sprint start by placing a foot on the back of the belt surface, thus allowing the subject to assume a typical standing split stance start position with their body leaning forward.

Data Collection and Processing

Instantaneous horizontal velocity was measured continuously with a radar device (Stalker ATS II, Texas, USA; 47 Hz), which was connected to a laptop running Stalker ATS System™ software (Version 5.0.2.1, Applied Concepts, Inc., Texas, USA) for data acquisition. The radar was positioned 10 m directly behind the sprint start position on a tripod set at a vertical height of 1 m to approximately align with the centre of mass of the sprinting subjects (Morin et al., 2006). The data file for each trial together with the height and body mass of each participant was imported into a custom-made LabVIEW (Version 13.0, National Instruments Corporation, Texas, USA) program that was used to calculate outcome variables consistent with procedures previously reported (Cross et al., 2015). Outcome variables included: F0; Pmax, S_{Fv} and split times for distances between 5 and 20 m. “Functional” values for F0, Pmax and S_{Fv} were calculated by dividing by BM; “effective” values for F0, Pmax and S_{Fv} were calculated by dividing by total system mass (i.e. BM plus added weight).

Maximum velocity (vmax) was determined as the peak speed achieved during the 30 m sprint. The velocity-time curve [v(t)] for each sprint was fitted to an exponential function:

$$v(t) = vmax * (1 - e^{-t/\tau})$$

Where t is the time and τ is the time constant. Instantaneous horizontal acceleration was calculated as the first derivative of the equation above and used to calculate F_h from Newton’s second law of motion:

$F_h(t) = [m * a(t)] + F_{air}(t)$

Where m is the body mass of the subject plus added WR and F_{air} is the air friction during sprinting, which is influenced by the frontal area of the subject (*Af*) (Arsac & Locatelli, 2002).

$Af = (0.2025 * height^{0.725} * m^{0.425}) * 0.266$

F0 and V0 were determined as the y-axis and x-axis intercepts of the force-velocity curve and were used to calculate Pmax and S_{Fv}:

$Pmax = (0.5*F0) * (0.5*V0)$

$S_{Fv} = - F0_{rel} / V0$

An Optojump system (Microgate, Italy; 1000 Hz) was positioned over the initial 15 m of each sprint and was used to determine the FT, CT, SL and SF of each step (Macadam, Simperingham, & Cronin, 2017). The Optojump system consists of a transmitting bar and a receiving bar containing 96 LEDs per metre. The bars were positioned in parallel on either side of the running lane and the duration of interruptions in communication between the bars was monitored to calculate the kinematic variables of interest. Sprint accelerations were split into the start phase (first 2 steps) and the acceleration phase (steps 3-8). Dependent variables were averaged over the two or six steps in each phase.

Sprints on the NMT were completed on a Woodway Force 3.0 (Eugene, OR, USA). Participants wore a waist belt with a rigid strap connecting the harness to a horizontal load cell at waist height (roughly the participants' centre-of-mass) directly behind the treadmill. The treadmill belt surface was manually stopped prior to the sprint start, enabling participants to assume a standing split stance position with their body leaning forward. Data collection occurred through the hardwired treadmill system interface (XPV7 PCB, Fitness Technology, Adelaide, Australia; 200 Hz). Consistent with methods previously reported post-processing of the data occurred in a custom-made LabVIEW software program that enabled the selection and analysis of each foot contact (Brughelli et al., 2011; Cross et al., 2014). Similar to the over-ground sprint analysis, the acceleration phase of treadmill sprints started from step three, but was averaged over 10 steps (steps 3-12) instead of just six over-ground steps (due to the limit of only have 15 m of Optojump track). Peak and mean values for F_v, F_h and PP were averaged over all ten foot contacts during the acceleration phase. Functional kinetic measures were normalised to BM, effective kinetic measures were normalised to total system mass.

Statistical Analyses

The mean and SD for all dependent variables was calculated for each set of two sprints. Repeated measures ANOVA with Bonferroni-adjusted post hoc comparisons were used to determine significant differences between the loading conditions. Changes with WR were discussed as a percent difference compared to the unloaded sprint condition. Cohen's d effect sizes (ES) were calculated to indicate the proportion of variance of the dependent variable that is explained by the independent variable. The strength of association between the variables were interpreted as trivial (0-0.19), small (0.20-0.59), moderate (0.60-1.19), and large (1.20-1.90) (Hopkins et al., 2009). Statistical significance was set at $p \leq 0.05$.

Results

All radar-derived variables are included in (Table 18). There was no significant change in sprint split times with 3% BM, but with 5% BM the time to cover 20 m was significantly increased by 1 to 2% compared to the unloaded (ES = 0.38) and 3% BM conditions (ES = 0.27). The heavy lower body WR condition (5% BM) resulted in a significant 6% reduction in effective Pmax (ES = 0.30) compared to the more moderately loaded condition (3% BM)**.** There was a significant main effect for effective *F0* but the post-hoc comparisons only indicated a trend (p = 0.097) towards a 4% higher level of horizontal force production with 3% BM compared to the unloaded condition. When functional *F0* with moderate lower body loading was analysed (8.7 ± 1.2 N/kg), *F0* was significantly higher by 9% compared to baseline (ES = 0.66). Considering F0 relative to V0, there was a significant 10% change in S_{Fv} towards a more force-dominant force-velocity profile with 3% BM compared to the unloaded condition (ES = 0.73), but no significant change (6%) was found with 5% BM.

Regarding step kinematics, during the start phase, FT, SF and SL were not significantly affected by the WR, but CT was significantly longer (5%; ES = 0.41-0.49) compared to baseline (

Table 19). During the acceleration phase phase, both CT (5 to 6%; ES [3% BM] = 0.56, ES [5% BM] = 0.72) and SF (-2 to -3%; ES [3% BM] = 0.32, ES [5% BM] = 0.52) were significantly altered compared to the unloaded condition.

From the NMT sprints, both peak and mean horizontal and vertical kinetic measures were determined from an average of steps 3 to 12 (Table 20). Peak effective F_h and PP were not significantly affected by the lower body WR during sprinting on the NMT, however the mean values for effective F_h and PP were significantly lower (-4 to -8%) in both loaded conditions compared to baseline. The effect sizes were small with the 3% BM condition (ES = 0.35 to 0.37), and also with the 5% BM condition (ES = 0.53-0.55). Both peak and mean effective F_v was 4% lower than baseline with 5% BM (ES = 0.66-0.70 respectively), but not significantly different with 3% BM compared to the unloaded sprints. Consistent with over-ground sprint results, the time to complete 0-10 m on the non-motorised treadmill was not significantly different with WR. There was a significant main effect ($p < 0.05$) for the time to complete 0-20 m on the treadmill, however the post hoc contrasts for these split times were not significant.

Table 18. Radar-derived data from 20 m sprints under the three loading conditions: 0, 3 and 5% BM. Effective measures (normalised to total system mass) are presented for all kinetic variables.

	0% BM	**3% BM**	**5% BM**
5 m (s)	1.35 ± 0.10	1.33 ± 0.11	1.36 ± 0.08
10 m (s)	2.13 ± 0.12	2.12 ± 0.13	2.15 ± 0.11
20 m (s)	3.46 ± 0.19	3.48 ± 0.18	3.53 ± 0.18 *#
F0 (N/kg)	8.0 ± 0.9	8.5 ± 1.1	8.1 ± 0.8
Pmax (W/kg)	16.8 ± 2.5	17.1 ± 2.5	16.1 ± 2.2 #
S_{Fv}	-0.99 ± 0.11	-1.09 ± 0.16 *	-1.05 ± 0.11

Note. * Denotes a significant difference compared to the 0% BM condition ($p \leq 0.05$); # Denotes a significant difference compared to the 3% BM condition ($p \leq 0.05$); BM = body mass; F0 = functional theoretical maximum horizontal force; Pmax = maximum functional horizontal power output; S_{Fv} = slope of the force-velocity curve

Table 19. Kinematic data from the start (steps 1-2) and acceleration (steps 3-8) sprint phases under the three loading conditions.

	0% BM	3% BM	5% BM
Start phase:			
FT (s)	0.062 ± 0.023	0.050 ± 0.015	0.051 ± 0.012
CT (s)	0.197 ± 0.021	0.206 ± 0.023 *	0.207 ± 0.020 *
SF (Hz)	4.00 ± 0.32	3.94 ± 0.30	3.92 ± 0.21
SL (m)	1.22 ± 0.13	1.23 ± 0.11	1.22 ± 0.11
Acceleration Phase:			
FT (s)	0.080 ± 0.010	0.077 ± 0.011	0.077 ± 0.012
CT (s)	0.157 ± 0.012	0.164 ± 0.013 *	0.166 ± 0.013 *
SF (Hz)	4.24 ± 0.21	4.17 ± 0.23 *	4.13 ± 0.21 *
SL (m)	1.60 ± 0.14	1.60 ± 0.13	1.59 ± 0.13

Note. * Denotes a significant difference compared to the 0% BM condition ($p \leq 0.05$); BM = body mass; FT = flight time; CT = contact time; SF = step frequency; SL = step length

Table 20. NMT-derived data from 20 m sprints under the three loading conditions. Effective measures (normalised to total system mass) are presented for all variables.

	0% BM	3% BM	5% BM
Peak F_v (N/kg)	22.4 ± 1.5	21.7 ± 1.7	21.5 ± 1.2 *
Mean F_v (N/kg)	12.7 ± 0.8	12.3 ± 0.7	12.2 ± 0.6 *
Peak F_h (N/kg)	3.91 ± 0.59	3.90 ± 0.70	3.88 ± 0.66
Mean F_h (N/kg)	2.34 ± 0.30	2.24 ± 0.27 *	2.19 ± 0.27 *#
PP (W/kg)	20.0 ± 3.2	19.9 ± 3.6	19.7 ± 3.6
MP (W/kg)	11.9 ± 1.7	11.3 ± 1.5 *	11.0 ± 1.6 *

Note. * Denotes a significant difference compared to the 0% BM condition ($p \leq 0.05$); # Denotes a significant difference compared to the 3% BM condition ($p \leq 0.05$); BM = body mass; F_v = vertical ground reaction force; F_h = horizontal ground reaction force; PP = horizontal peak power output; MP = horizontal mean power output

Discussion and Implications

This was the first study to include an assessment of the acute impact of heavy (5% BM) lower body WR during over-ground sprinting, and the first study to assess the acute impact of moderate (3% BM) lower body WR during treadmill sprinting. The key findings that relate to the study hypotheses about sprinting with lower body WR compared to unloaded sprinting were: 1) over-ground sprint times were not significantly slower over the initial 10 m, even with heavy lower body WR; 2) ground CT was longer and SF was shorter with lower body WR, but FT and SL were statistically unchanged; 3) mean effective horizontal kinetic measures were significantly lower during treadmill sprints with all lower body WR conditions compared to unloaded sprints; and, 4) vertical forces were only significantly altered with the heavier loading condition.

Short-distance (20 m) sprint split times were not significantly changed by the moderate lower body loading. Heavier lower body loading similarly resulted in unchanged split times over the initial 10 m, but participants were significantly slower over 20 m compared to both the unloaded and 3% BM conditions. The added lower body loading appears to have been well tolerated during the leg pumping or "piston-like" action of the acceleration phase. These findings are consistent with previous research involving over-ground sprinting with 3% BM (Macadam, Simperingham, & Cronin, 2017) and treadmill sprinting with 5% BM (Simperingham & Cronin, 2014) which found no significant changes over the initial 10 m. Additionally, Macadam, Simperingham, and Cronin (2017) found no significant impact of WR loading (3% BM) on the anterior aspect of the legs compared to the posterior aspect of the legs.

Changes in sprint step kinematics with lower body WR in the present study were generally consistent with previous findings, with longer ground CT and lower SF during the acceleration phase (Macadam, Simperingham, & Cronin, 2017; Ropret et al., 1998; Simperingham & Cronin, 2014). Moreover, in agreement with the aforementioned studies, FT and SL were unchanged with either magnitude of WR in this study. Therefore, it appears that 3-5% BM lower body loading during maximum effort sprinting can be used to overload different mechanical aspects of sprint-running performance. In contrast, during constant pace running (14 km/h [3.9 m/s]) FT, CT, SF and SL were not significantly affected by lower body WR loading up to 5% BM (Couture et al., 2018). Couture et al. (2018) hypothesised that gait patterns were maintained by the neuromuscular system increasing muscular output in order to sustain biomechanical efficiency. However, at a certain loading magnitude or position, the change in inertia with WR cannot be overcome by simply increasing muscular output and the gait pattern is altered. In the case of constant pace running, that magnitude and position of WR was whole body loading equivalent to 10% BM, resulting in a significant 3% increase in ground CT. In the case of sprinting it appears that lower body loading as low as 3% BM will overwhelm any increase in muscular activity and result in some changes in the baseline general performance descriptors of the acceleration phase.

Substantial changes in sprint mechanics with WR may be deleterious to sprint-running technique, but the magnitude of the measured aspects of step kinematic changes recorded in the present study did not exceed 6% for any loaded condition. It is hypothesised that changes of this magnitude are sufficiently subtle to ensure the similarity of unloaded and loaded sprint movement patterns and therefore theoretically ensure a level of specificity of training and subsequent transfer of WR training to sprint performance (Bosch, 2016; Brearley & Bishop, 2019). The findings therefore provide initial support for the use of lower body loading up to 5% BM during the acceleration phase. Furthermore, given that velocity is a product of SL and SF, the overloading of SF without altering SL with WR, suggests this form of loading may be a suitable training method to improve these key determinates of speed. Longitudinal training interventions are required to assess the chronic benefits of such WR loading protocols.

Consistent with the study hypotheses, peak horizontal kinetic values were statistically unchanged during the acceleration phase of treadmill sprinting, but mean values for F_h and PP were significantly lower with WR. Peak horizontal power output was also significantly reduced during acceleration phase over-ground sprinting with the heavier WR condition, however the radar-derived calculation of F0 was unchanged. Higher horizontal force production during acceleration is associated with better sprint performance (Kugler & Janshen, 2010; Rabita et al., 2015). Compared to unloaded sprinting, $F0_{rel}$ was significantly higher with 3% BM, but no different to baseline with 5% BM. When the horizontal force data was expressed relative to total system mass, the same trend was apparent, although the specific contrasts did not achieve statistical significance. These results indicate that a lower body WR load equivalent to 3% BM may intrinsically reinforce the importance of horizontal force production during the acceleration phase. With heavier loading (5% BM), early acceleration speed and F0 were still maintained compared to baseline, however PP was reduced compared to the more moderately loaded condition (3% BM). Presumably the power output reduction was due mainly to the reduced sprinting velocity after the initial 10 m. The tendency towards reduced horizontal kinetics with heavy WR may indicate a reprioritisation of a greater magnitude of GRF being directed in a vertical direction in order to provide sufficient time for the repositioning of the heavier lower limbs. It may be hypothesised that subjects more accustomed to sprinting with WR or those with more developed acceleration mechanics could better tolerate the heavier loading conditions. The relative slope of the force velocity profile was also significantly shifted to a more force-dominant profile with the moderate lower body WR. This finding reinforces the proposal that this form of WR may be well suited to those individuals aiming to shift the high force portion of their force-velocity-power profile (Samozino et al., 2012).

Hunter et al. (2005) concluded that relative propulsive impulse explained 57% of the variance in short sprint velocity. The reduced SF and increased CT observed in the present study would facilitate greater impulse application with WR, which would be required to maintain speed over the initial 10 m. Horizontal impulse was not calculated in the current study, but the results indicate that the reduced mean horizontal GRF acting over a longer ground CT was likely insufficient to increase horizontal impulse enough between the 10 m and 20 m marks in the heavy loaded condition and therefore sprint velocity was reduced. The reduced average F_h during treadmill sprinting may appear contradictory to the F0 results in the present study, however it should be noted that the moment of expression of F0 will occur at the very beginning of a sprint, while the horizontal data from treadmill sprints summarises the phase of 10 steps from step 3 to step 12.

Consistent with the study hypotheses, functional peak and mean F_v was unchanged compared to unloaded sprinting, but effective peak and mean F_v was actually lower than baseline with the heavier lower body loading condition. Conversely, Simperingham and Cronin (2014) previously reported no significant change in effective F_v and significantly higher absolute F_v during the acceleration phase of a treadmill sprint with 5% BM. The differences between the studies can at least partly be explained by the difference in the physical capacities of the participants. The participants in the current study were all currently competitive rugby players, on average 10 years younger and 27% faster over 20 m compared to the participants in the earlier study. While lower body WR up to 6% BM during vertical jumping resulted in no significant change in effective F_v (Macadam, Simperingham, Cronin, et al., 2017), lower body loading (5% BM) during treadmill running (at 14 km/h) also led to a significant decrease in effective F_v (Couture et al., 2018). Couture et al. (2018) suggested that the placement of WR on the major muscles involved in running may have caused greater pre-activation of the muscles, leading to greater attenuation of the impact forces.

In the absence of a running track with a series of in-ground force plates, the NMT was utilised in this study to obtain some horizontal and vertical kinetic variables. An acknowledged limitation is that treadmill and over-ground sprinting differ (Simperingham, Cronin, & Ross, 2016), so caution should be taken with inferences made about over-ground sprinting from treadmill sprinting data. Future research should replicate the current study but utilising in-ground force plates to quantify all kinetic variables. Additionally, future research could utilise electromyography (EMG) to quantify changes in muscle activation with WR. In the only WR study to date to utilise EMG, authors reported no change in hamstring muscle activity during 40 sprints with light lower body WR (< 2% BM) (Hurst et al., 2018). Further EMG analysis is warranted with heavier WR loads and including different muscle groups, such as the hip flexors. Hip flexor moment is related to sprint velocity (Ema et al., 2018), and specifically overloading the hip flexors is theoretically an efficacious use of lower body WR training.

The acceleration sprint phase was the focus of the current study, but lower body WR of 3 to 5% BW may be relatively more influential to sprint biomechanics during the more “pendulum-like” action of the maximum velocity phase. Future research is required with WR loads above 3% BM during the maximum velocity sprint phase. Moreover, the effects of WR on joint kinematics are beyond the scope of this paper but should be investigated in future research.

Conclusions

Lower body WR (3 to 5% BM) provided an overload to the sprint acceleration phase for field-based team sport athletes to the extent that ground CT was significantly increased and SF was significantly decreased. Moderate WR loading (3% BM) resulted in increased functional F0 and combined with likely increased muscular activity resulted in unchanged 20 m sprint time compared to unloaded sprinting. Heavier WR loading (5% BM) resulted in a significant decrease in both effective F_v and 20 m sprint time. Sprint acceleration biomechanics were changed by no more than 6% with WR loading up to 5% BM. Such loading configurations can therefore provide specific overload without substantially altering sprint mechanics. Longitudinal research is required to fully understand the efficacy of this training technique on sprint acceleration.

CHAPTER 9

CHANGES IN MAXIMUM VELOCITY PHASE BIOMECHANICS DURING OVER-GROUND AND TREADMILL SPRINTING WITH LOWER BODY WEARABLE RESISTANCE

This paper comprises the following paper submitted to *Sports Biomechanics*:

Simperingham, K. D., Cronin, J. B., Ross, A., Brown, S. R., Macadam, P. & Pearson, S. (2019). Changes in maximum velocity phase biomechanics during over-ground and treadmill sprinting with lower body wearable resistance. *Sports Biomechanics, [In review]*.

Prelude

Noticeable differences were apparent in the previous chapter between moderate (3% BM) and heavy (5% BM) lower body WR during acceleration phase sprinting. While both loading magnitudes resulted in increased ground CT (5-6%) and decreased SF (-2 to -3%), 3% BM WR resulted in increased (9%) functional F0 and unchanged 20 m sprint times. 5% BM WR on the other hand resulted in a significant decrease (-4%) in effective F_v and slower (-1 to -2%) 20 m sprint times. These findings lead to the question of how the same magnitudes of WR would affect the maximum velocity phase of sprinting. Based on the biomechanical differences between the acceleration phase and the maximum velocity phase, it was expected that the same WR loading may have more affect during the maximum velocity phase.

Introduction

Frequent short sprints are common in field-based team sports (Gabbett, 2012; Lindsay et al., 2015; Ross et al., 2015; Spencer et al., 2005; Vigne et al., 2010), however anecdotally, the less frequent sprint efforts that are closer to maximum velocity can be critical in some of the most influential plays in sports such as rugby, American football and soccer. The majority of sprints in rugby union and rugby league start from a moving start position (walking, jogging or striding), so although sprints may be short in duration or distance the percentage of maximum speed achieved can be relatively high (Duthie, Pyne, Marsh, & Hooper, 2006; Gabbett, 2012). Maximum velocity phase training for team sport athletes is therefore important, particularly for certain positional groups. The team sport reverence for athletes with exceptional maximum velocity capacities has been highlighted by the successful transfer of elite sprinters to professional rugby and American football athletes. Some conjecture surrounds optimal sprint training methods for developing maximum velocity capabilities (Bolger et al., 2015; Rumpf et al., 2016), but interest in the area from physical performance coaches remains very high.

The acceleration phase and the maximum velocity phase of sprint-running are biomechanically different (Nagahara et al., 2019; Nagahara et al., 2014; von Lieres Und Wilkau et al., 2018; Yu et al., 2016) and distinct emphases are required when training to improve the respective phases (Blazevich & Jenkins, 2002; Bolger et al., 2015; Lloyd et al., 2016; Lockie et al., 2012; Rumpf et al., 2016). The acceleration phase is characterised by a forward leaned body position and a linear, "piston-like" pumping action of the legs where the GRF is directed in a horizontal direction as much as possible (Hunter et al., 2005; Kawamori, Nosaka, et al., 2013; Rabita et al., 2015). In contrast, the maximum velocity phase involves a more upright body position, a more circular "pendulum-like" leg motion where improved performance is associated with shorter ground CT, longer SL and higher vertical stiffness (Bret et al., 2002; Chelly & Denis, 2001; Kugler & Janshen, 2010; Mann, 2011; Nagahara & Zushi, 2017). Consensus has not yet been reached as to whether the horizontal or vertical component of the GRF is most important in achieving faster running speeds during the maximum velocity phase (Brughelli et al., 2011; Morin et al., 2012; Nagahara et al., 2019; Nummela et al., 2007; Weyand et al., 2000).

WR is a training tool that can be used to specifically overload elements of the sprint cycle (Dolcetti et al., 2018; Macadam, Cronin, et al., 2017), with recent research interest focusing on the acute impact of lower body WR during sprinting (Macadam, Simperingham, & Cronin, 2017; Simperingham & Cronin, 2014). Ropret et al. (1998) reported a 13% decrease in vmax with lower body loading equivalent to approximately 5% BM attached just above the ankle (i.e. 2.5% BM per leg). All other assessments of lower body WR during the maximum velocity phase of over-ground sprinting involved lighter (≤ 2% BM added weight) or more proximal loading configurations attached to the shank (Feser et al., 2018; Hurst et al., 2018; Zhang et al., 2018), thigh (Feser et al., 2018; Hurst et al., 2018) or whole leg (Bennett et al., 2009). Light loading on the shank or thigh also resulted in a significant decrease in maximum velocity (≤ 2%) (Feser et al., 2018; Hurst et al., 2018; Zhang et al., 2018), but when the load (equivalent to 2% BM) was spread across the whole leg the decrease in velocity was more than twice as much (5%) (Bennett et al., 2009). When spatiotemporal values were measured during the maximum velocity phase, ground CT was longer and SF was lower with the WR (Feser et al., 2018; Hurst et al., 2018) although this trend was not significant in the study of Bennett et al. (2009).

The only analysis of changes in maximum velocity sprint phase kinetics with WR was completed on a NMT with heavy lower body loading equivalent to 5% BM (Simperingham & Cronin, 2014). F_h and PP were not significantly altered by the WR, which was spread across the thigh and shank. Peak F_v was significantly higher (5%), although only when analysed in absolute terms rather than relative to BM. Consistent with the over-ground studies, maximum velocity (-5%) and SF (-4%) were significantly decreased, while ground CT was increased (5%). No studies to date have reported either kinematic changes with lower body WR greater than 2% BM, or kinetic changes with less than 5% BM during maximum velocity phase sprinting. A clearer understanding of the changes in maximum velocity phase sprint biomechanics with lower body WR is necessary to prescribe optimal sprint training interventions.

The aim of this study was to quantify the kinematic changes that occur during the maximum velocity phase of over-ground sprinting with 3% and 5% BM added lower body WR. A secondary aim was to quantify both the horizontal and vertical kinetic changes during treadmill sprinting under the same loaded conditions. It was hypothesised that over-ground results would replicate earlier findings with significantly lower maximum velocity achieved even with moderate WR loading, and that these changes would be associated with longer ground CT and lower SF. It was further hypothesised that there would be no change in relative F_h, F_v or PP. The purpose of the study was to achieve an improved understanding of how lower body WR acutely impacts sprint biomechanics, and therefore inform recommendations for the use of WR for maximum velocity sprint training.

Methods

Participants

Fifteen male rugby union athletes (19.0 ± 0.5 years; 181.2 ± 7.3 cm; 91.0 ± 17.4 kg) volunteered for this study. All participants completed the over-ground sprint procedures. On a separate day, a subset of ten of the athletes (18.9 ± 0.4 years; 182.2 ± 6.5 cm; 96.6 ± 18.5 kg) also completed the NMT sprints. Participants were requested to not complete any high intensity training in the 24 hours prior to testing sessions and to present to the testing session well hydrated and having not eaten at least 90 minutes prior to the start of testing. Participants had no previous experience with sprinting with lower body WR. Approval for the study was obtained from the institutional research ethics committee and participants provided written informed consent prior to participating in the study.

Procedures

Participants completed three sets of two 30 m sprints on an indoor running track and on a separate day completed three sets of two 30 m sprints on a Woodway Force 3.0 (Eugene, OR, USA) NMT. Procedures for testing on the treadmill and post-processing of the treadmill-derived data was consistent with procedures previously reported by (Brown, Brughelli, & Cross, 2016). Over-ground and treadmill sprint testing sessions were completed in a randomised order. The 20 m to 30 m section of the over-ground sprints was analysed as a representation of the maximum velocity sprint phase (Mann, 2011). Three WR conditions were compared: unloaded (0% BM); moderate lower body loading (3% BM); and, heavy lower body loading (5% BM). The WR was attached with Velcro to Lila™ Exogen™ compression-based pants and calf sleeves (Sportboleh Sdh Bhd, Malaysia). The load was evenly distributed between the anterior and posterior aspects of the thigh and shank (respectively 2/3 and 1/3 of the total added weight) (Figure 12). Loading conditions were presented in a randomised order with five minutes of passive recovery between sprint repetitions and between sets.

Figure 12. Exogen compression-based pants and calf sleeves with added weight attached.

Prior to the warm-up participants put on the Exogen™ pants and calf sleeves and wore them throughout the testing session. Height and body mass were recorded without shoes. A 20-minute standardised warm-up was completed on an indoor track (including jogging, sprint drills, dynamic stretching and build-up sprints of increasing intensity up to maximal effort). Prior to the treadmill sprints, participants completed the same standardised over-ground warm-up and then a further treadmill-specific warm-up on the NMT involving: a 30 s constant pace jog, finishing with one acceleration run up to approximately 75% effort; two 6 s sprints at 75-80% effort from a stationary start; two 3 s sprints at greater than 90% effort from a stationary start. After the warm-up there was a period of five minutes of passive rest to ensure full recovery. A “blocked” sprint start position was used, involving the experimenter manually stopping any belt movement prior to the sprint start by placing a foot on the back of the belt surface, thus allowing the subject to assume a typical standing split stance start position with their body leaning forward.

Data Collection and Processing

The time to cover the 20 m to 30 m section of the over-ground sprint was recorded with photoelectric cells (Swift Speedlink, Swift Performance Equipment, Australia) (coefficient of variation ~1%; typical error ~0.02 s) (Cronin & Templeton, 2008), and was used to determine the maximum velocity achieved during the sprint. Instantaneous horizontal velocity was measured continuously with a radar device (Stalker ATS II, Texas, USA; 47 Hz), which was connected to a laptop running Stalker ATS System™ software (Version 5.0.2.1, Applied Concepts, Inc., Texas, USA) for data acquisition. The radar was positioned 10 m directly behind the sprint start position on a tripod set at a vertical height of 1 m to approximately align with the centre of mass of the sprinting subjects (Morin et al., 2006). V0 was determined as the x-axis intercept of the force-velocity curve (coefficient of variation = 2%; intraclass correlation coefficient = 0.92), using procedures previously reported (Cross et al., 2015; Simperingham et al., 2019), and vmax was determined as the peak instantaneous speed recorded with radar during the 30 m sprint.

The 20 m to 30 m section of the sprint was recorded with high speed video (Sony RX 10, Sony, Japan; 300 Hz) using a camera positioned perpendicular to the 25 m mark on the track, at a distance of 10 m from the middle of the track. Video files were manually analysed by one researcher to identify the timing of touchdown and toe-off for two complete stride cycles. This information together with the 20 to 30 m split time was used to calculate mean FT, CT, SF and SL and kvert. Kvert was determined based on the spring-mass paradigm using CT, FT and the BM of each participant (Macadam, Simperingham, & Cronin, 2017; Morin, Dalleau, Kyröläinen, Jeannin, & Belli, 2005):

$$kvert = Fmax/\Delta y$$

Where Fmax is the maximum vertical GRF during contact (in N) and Δy is the vertical displacement (in m) of the centre of mass when it reaches its lowest point:

$Fmax = BM*g\pi/2(FT/CT+1)$

$\Delta y = Fmax*CT^2/BM\pi^2 + gCT^2/8$

Where *g* is the acceleration constant due to gravity. A four-step average was determined from each sprint for each of the video-derived variables.

Sprints on the NMT were completed on a Woodway Force 3.0. Participants wore a waist belt with a rigid strap connecting the harness to a horizontal load cell at waist height directly behind the treadmill. The treadmill belt surface was manually stopped prior to the sprint start, enabling subjects to assume a standing split stance position with their body leaning forward. Data collection occurred through the hardwired treadmill system interface (XPV7 PCB, Fitness Technology, Adelaide, Australia; 200 Hz). Consistent with methods previously reported, post-processing of the data occurred in a custom-made LabVIEW software program that enabled the selection and analysis of each foot contact (Brughelli et al., 2011; Cross et al., 2014). The maximum velocity phase of treadmill sprints started from step 13 and was averaged over 10 steps (steps 13 to 22). This was consistent with previous sprint research (Brown et al., 2017; Simperingham & Cronin, 2014), and with authors that have proposed that the maximum velocity phase starts when participants reach 80% of their maximum velocity, after approximately 10 steps in a sprint race (Mann, 2011). Peak and mean values for F_v, F_h and PP were averaged over all ten foot contacts during the maximum velocity phase. Functional kinetic measures were normalised to BM, effective kinetic measures were normalised to total system mass.

Statistical Analyses

The mean and SD for all dependent variables were calculated for each set of two sprints. Repeated measures ANOVA with Bonferroni-adjusted post hoc comparisons were used to determine significant differences between the loading conditions. Changes with WR were discussed as a percent difference compared to the unloaded sprint condition. Cohen’s d effect sizes (ES) were calculated to indicate the proportion of variance of the dependent variable that is explained by the independent variable. The strength of association between the variables were interpreted as trivial

(0-0.19), small (0.20-0.59), moderate (0.60-1.19), and large (1.20-1.90) (Hopkins et al., 2009). Statistical significance was set at $p \leq 0.05$.

Results

Speed, step kinematics and vertical stiffness data are summarised in Table 21 for the three different lower body WR conditions. Lower body WR resulted in a significant increase in the time to cover the 20 to 30 m sprint (3% BM: 3.9%, ES = 0.46; 5% BM: 5.4%, ES = 0.78) as well as a significant decrease in the maximum velocity achieved (3% BM: -3.0%, ES = 0.48; 5% BM: -5.0%, ES = 0.83). For the 20-30m split time, vmax and V0, percentage decrement in performance was approximately equivalent to the magnitude of the lower body loading relative to participant body mass (i.e. 3 to 5%). In all cases the effect sizes were small with 3% BM lower body loading (ES = 0.46 to 0.52) and the effect sizes were moderate with 5% BM lower body loading (ES = 0.77 to 0.83).

No statistically significant changes in FT or FT/CT were found with either WR condition compared to unloaded sprinting, however, CT was significantly longer (3% BM: 4.0%, ES = 0.40; 5% BM: 4.7%, ES = 0.45), SF was significantly lower (3% BM: -2.6%, ES = 0.53; 5% BM: -3.1%, ES = 0.69) and effective kvert was also significantly lower (3% BM: -8.1%, ES = 0.39; 5% BM: -8.9%, ES = 0.40) than during unloaded sprinting. SL was only significantly lower with the heavy loading condition (-1.8%, ES = 0.25).

Both peak and mean horizontal and vertical kinetic measures were determined from an average of steps 13 to 22 during the treadmill sprints (Table 22). The moderate loading condition resulted in no statistically significant ($p > 0.05$) differences in effective kinetic measures compared to baseline. The heavy loading condition resulted in significantly lower mean effective F_h (-5.1%, ES = 0.40) and mean effective PP (-7.6%, ES = 0.54). Mean F_v data (expressed in effective or functional terms) was not significantly different with WR, but peak F_v was significantly higher in both absolute terms (3.1-3.6%, ES = 0.16-0.18) and relative to body mass (3.2-3.7%, ES = 0.32-0.39) with both loading conditions. Absolute mean F_v was also significantly higher (2.8%, ES =

0.15), but only with the heavy lower body WR. Consistent with over-ground results, treadmill vmax was significantly slower under both loading conditions (3% BM: -1.8%, ES = 0.37; 5% BM: -2.7%, ES = 0.54), but CT was only significantly longer (3.1%, ES = 0.67) during treadmill sprints with 5% BM WR.

Table 21. Kinematic data from maximum velocity phase sprints (20-30 m) under the three loading conditions. Effective measures (normalised to total system mass) as presented for all kinetic variables.

	0% BM	**3% BM**	**5% BM**
20-30 m (s)	1.22 ± 0.07	1.26 ± 0.10 *	1.29 ± 0.09 *#
vmax (m/s)	8.21 ± 0.45	7.97 ± 0.57 *	7.81 ± 0.52 *#
V0 (m/s)	8.44 ± 0.56	8.13 ± 0.60 *	8.02 ± 0.52 *
FT (s)	0.123 ± 0.011	0.125 ± 0.009	0.126 ± 0.012
CT (s)	0.117 ± 0.011	0.122 ± 0.012 *	0.123 ± 0.013 *
FT/CT	1.06 ± 0.17	1.04 ± 0.14	1.04 ± 0.18
SF (Hz)	4.17 ± 0.20	4.06 ± 0.22 *	4.03 ± 0.18 *#
SL (m)	1.98 ± 0.13	1.97 ± 0.13	1.94 ± 0.15 *
SL/Ht	1.09 ± 0.07	1.08 ± 0.07	1.07 ± 0.07 *
kvert (kN/m/kg)	0.54 ± 0.12	0.49 ± 0.10 *	0.49 ± 0.12 *

Note. * Denotes a significant difference compared to the 0% BM condition ($p \leq 0.05$); # Denotes a significant difference compared to the 3% BM condition ($p \leq 0.05$); BM = body mass; vmax = maximum velocity (from timing lights); V0 = theoretical maximum velocity (from radar); FT = flight time; CT = contact time; SF = step frequency; SL = step length; Ht = participant standing height; kvert = vertical stiffness

Table 22. NMT-derived kinetic data from the maximum velocity phase (steps 13-22) of 30 m treadmill sprints under the three loading conditions: 0, 3 and 5% added weight. Effective measures (normalised to total system mass) are presented for all variables.

	0% BM	**3% BM**	**5% BM**
Peak F_V (N/kg)	22.3 ± 2.2	23.3 ± 2.3	23.0 ± 2.1
Mean F_V (N/kg)	13.4 ± 1.0	13.2 ± 1.0	13.1 ± 0.9
Peak F_h (N/kg)	3.35 ± 0.50	3.33 ± 0.57	3.31 ± 0.63
Mean F_h (N/kg)	1.92 ± 0.25	1.86 ± 0.24	1.83 ± 0.23 *
PP (W/kg)	19.4 ± 2.9	19.0 ± 3.5	18.7 ± 3.7
MP (W/kg)	11.0 ± 1.6	10.5 ± 1.6	10.2 ± 1.5 *

Note. * Denotes a significant difference compared to the 0% BM condition ($p \leq 0.05$); # Denotes a significant difference compared to the 3% BM condition ($p \leq 0.05$); BM = body mass; F_V = vertical ground reaction force; F_h = horizontal ground reaction force relative to system mass; PP = peak horizontal power output relative to system mass; MP = mean horizontal peak power output

Discussion and Implications

This was the first study to assess kinematic changes during maximum velocity sprinting with lower body WR greater than 2% BM added weight, and the first study to assess kinetic changes during maximum velocity sprinting with less than 5% BM added weight. The key findings that relate to the study hypotheses about sprinting with lower body WR compared to unloaded sprinting were: 1) maximum sprinting speed was significantly reduced with WR, and the percentage decrement in performance was approximately equivalent to the magnitude of the lower body loading relative to participant body mass (i.e. 3-5%); 2) statistically significant kinematic changes included longer CT, lower SF and lower effective kvert with loading ≥ 3% BM, and also shorter SL with 5% BM; and, 3) 3% BM lower body WR resulted in no statistically significant changes in effective horizontal or vertical kinetic measures, but mean effective F_h and PP was significantly lower with 5% BM lower body WR.

The reduction in maximum sprinting speed was approximately 3% with moderate WR loading (3% BM) and approximately 5% with heavy WR loading (5% BM). Authors of three previous studies involving the analyses of lighter lower body loading (~ 2% BM) also reported decrements in maximum sprinting speed (~ 2%) that were equivalent to the relative magnitude of the lower body loading (Feser et al., 2018; Hurst et al., 2018; Zhang et al., 2018). The disproportionately large decrement in maximum sprinting speed (-13%) reported in one study (Ropret et al., 1998) was probably due to the distal positioning of the heavy WR (5% BM) increasing the rotational inertia workload, rather than being spread across the entire leg as was the case in the current study. Previously researchers demonstrated that split times were not significantly impaired over the first 10 m of the acceleration phase of a sprint with lower body WR up to 5% BM, however split times between 10 m and 20 m were impaired (-2% to -3%) even with moderate lower body WR (3% BM) (Macadam, Simperingham, & Cronin, 2017; Simperingham & Cronin, 2014). The difference in findings between the acceleration phase and the maximum velocity phase can likely be attributed to the differences in biomechanics between the sprint phases. The lower body loading was tolerated well during the linear, pumping action of the earlier acceleration phase, however the WR had a greater impact on the more circular motion of the comparatively upright maximum velocity phase, even with moderate loading magnitudes. This differential adaptation can most likely be explained by the increased movement velocity and limb angular velocity during the maximum velocity phase, which results in greater angular momentum and kinetic energy and hence greater muscular work requirements of the involved musculature as compared to the acceleration phase. Additionally, relatively long ground CT can still be associated with relatively fast early acceleration performance, but shorter CT are associated with faster maximum velocity performance (Mann, 2011). A greater impact of longer CT with WR is therefore expected on maximum velocity phase performance compared to early acceleration phase performance.

In spite of the biomechanical differences between the acceleration and maximum velocity sprint phases, the changes in CT (4-5%) and SF (-3%), together with unchanged FT in the current study were consistent with acceleration phase changes previously reported (Macadam, Simperingham, & Cronin, 2017; Ropret et al., 1998; Simperingham & Cronin, 2014). Interestingly, there was a small significant reduction in SL (-2%) during the maximum velocity phase (with 5% BM WR only), which contrasts with no significant change in SL during previous analyses with the same magnitude of heavy lower body WR during acceleration phase sprinting (Macadam, Simperingham, & Cronin, 2017; Simperingham & Cronin, 2014), NMT sprinting (acceleration phase and maximum velocity phase) (Simperingham & Cronin, 2014), or constant pace running (at 14 km/h) (Couture et al., 2018). Again, the increase in angular velocity of the maximum velocity phase in tandem with the greater angular momentum associated with the additional mass most likely explains the differences between studies. The changes in step kinematics were all within 5% of baseline. It is hypothesised that changes of this magnitude are sufficiently subtle to ensure the similarity of unloaded and loaded sprint movement patterns and therefore theoretically ensure a level of specificity of training and subsequent transfer of WR training to sprint performance (Bosch, 2016; Brearley & Bishop, 2019)Therefore, it could be proposed that WR up to 5% BM can be used as a specific maximum speed training technique without being substantially deleterious to sprint technique. Although, given that velocity is a product of SL and SF, the overloading of SF without altering SL with 3% BM WR, suggests this form of moderate loading may be a more suitable training method (compared to heavier loading) to improve these key determinates of speed.

Higher kvert is related to higher maximum sprinting speed (Bret et al., 2002; Chelly & Denis, 2001; Nagahara & Zushi, 2017) and in this study kvert was significantly decreased (-8% to -9%) with lower body WR. CT, FT and BM were used to determine kvert (Morin et al., 2005), with the significant increase in CT combined with unchanged FT leading to the substantially lower kvert. The WR probably resulted in increased hip, knee or ankle flexion during the longer ground contact period, however three-dimensional analysis of sprinting with lower body WR is required to confirm this contention. Increased effort to maintain baseline CT while sprinting with light to moderate WR may be an effective specific training technique with the aim of chronically increasing kvert and therefore potentially increasing maximum velocity. Systems that enable real time feedback on CT (e.g. Optojump; Microgate, Italy) could be effective when individual CT targets are set for WR training sessions.

While sprint kinematics were significantly altered with both moderate and heavy lower body WR, vertical effective sprint kinetics (i.e. relative to total system mass) were statistically unchanged and horizontal effective sprint kinetics were only significantly changed with 5% BM. Heavy lower body WR lead to significantly lower mean effective F_h (-5%) and mean effective PP (-8%). A consistent pattern of reduced horizontal effective kinetic data was evident with 3% BM WR, however the post-hoc contrast was not significant ($p > 0.05$). The reduced horizontal mean force and power is consistent with the significant reduction in maximum velocity. However, this would make more sense if a simultaneous increase in mean effective F_v was recorded (indicating a greater proportion of total GRF being directed in the vertical direction due to the heavy WR condition). Peak F_v was only significantly higher in absolute terms (3-4%) and relative to BM (functional) (3-4%) with both loading conditions, but the higher GRF appears to have been a function of the added weight only rather than any additional muscular effort, as the magnitude of effective F_v was unchanged by the additional loading. An absolute increase in peak F_v was required to account for the WR, but mean F_v was not significantly altered due to the concomitant increase in CT. Simperingham and Cronin (2014) also reported significantly higher absolute F_v and statistically unchanged effective F_v with the same magnitude of heavy lower body WR. Absolute horizontal sprint kinetic results were also statistically unchanged in this earlier study, and although not reported, changes in effective F_h (-3.1%) and effective PP (-7.7%) were consistent with the present study.

The results of this study are applicable to a population of young rugby players with little to no experience of sprinting with lower body WR. Practitioners should be mindful that results may vary for different athletic populations and after a longer period of familiarisation with WR training. Instrumented NMT enable analysis of every step during a sprint, however results can differ from over-ground sprinting (Simperingham, Cronin, & Ross, 2016). Future research should address this limitation by analysing lower body WR during over-ground sprinting on in-ground force plates. Combining three-dimensional motion analysis of joint kinematics and electromyography of key lower body muscles would also enhance the understanding of the impact of WR during sprinting.

Conclusions

Lower body WR (3-5% BM) worn during the maximum velocity sprint phase resulted in significantly increased ground CT, and significantly decreased SL (heavy WR only) and SF. The percentage decrement in maximum sprint velocity was approximately equivalent to the magnitude of the lower body loading relative to participant body mass (i.e. 3-5%). Horizontal effective sprint kinetics were only significantly reduced with heavy WR. So lower body WR is a specific speed training tool that can overload maximum velocity phase CT, SF and at heavy loads also overload SL and F_h production. Additionally, it was proposed that sprinting with $\leq$ 3% BM WR may be an effective specific training technique for chronically increasing vertical stiffness and therefore potentially increasing maximum velocity. Longitudinal research should assess the chronic impact of the acute changes summarised in this study.

CHAPTER 10

ACUTE CHANGES IN SPRINT-RUNNING PERFORMANCE FOLLOWING BALLISTIC EXERCISE WITH ADDED LOWER BODY LOADING

This paper comprises the following paper published in *Journal of Australian Strength and Conditioning*:

Simperingham, K. D., Cronin, J. B., Pearson, S. & Ross, A. (2015). Acute changes in sprint running performance following ballistic exercise with added lower body loading. *Journal of Australian Strength and Conditioning*, 23(6), 86-89.

Prelude

Sprint velocity during the maximum velocity phase was reduced (-3% to -5%) approximately linearly as WR increased from 3% BM to 5% BM. Lower body WR significantly overloaded ground CT (4-5%), SL (-2%; 5% BM WR only), SF (-3%), vertical stiffness (-8 to -9%) and treadmill-derived horizontal effective sprint kinetics (-5 to -7%; 5% BM WR only) during the maximum velocity phase. Before testing the chronic impact of a longitudinal lower body WR training intervention (Chapter 11), the next chapter involves addressing earlier findings (Chapter 6 and Chapter 7) about the potential for APE of sprint performance 4 to 15 minutes after loaded BE. A single subject research design was used to compare a range of different loaded ballistic exercise stimuli. A single subject research design involves the use of a quantitative research paradigm for exploratory research with small sample sizes (in this case n = 1) (Backman, Harris, Chisholm, & Monette, 1997). The unit of study is the individual rather than a group. Relatively large changes compared to repeated individual baseline measurements are deemed "substantial". Substantial effects can be investigated in future research with larger sample sizes. An intended outcome of the study was to generate potentially effective WR training interventions to be used in the training study in Chapter 11.

Introduction

APE or PAP of power performance is often studied following conditioning stimuli involving a heavy resistance exercise such as a back squat with a 1-5 repetition maximum load (e.g. Mitchell & Sale, 2011). However, pairing heavy resistance exercise and sprint-running has logistical limitations, so recent research attention has also focused on ballistic exercise (e.g. jumps, modified Olympic lifts and dynamic warm-ups) as conditioning stimuli that may elicit APE of sprint performance (for review see Maloney et al., 2014).

Potentiation and fatigue interact after a conditioning stimulus (Sale, 2002). The optimal recovery time after a conditioning stimulus to achieve PAP of sprint performance is dependent on the physical characteristics of the subject (e.g. strength level, muscle fibre type composition, training age and gender) and the intensity, volume and type of the conditioning stimulus selected (Maloney et al., 2014; Sale, 2002). Ballistic exercise results in reduced fatigue compared to heavy resistance exercise and therefore the time course of the PAP response will change dependent on the conditioning stimulus used (Gilbert & Lees, 2005) (Figure 9, p. 101). Researchers reported an acute enhancement in sprint performance after 2-3 sets of drop jumps or single leg bounds (Lima et al., 2011; Turner et al., 2015), but not after a single set of tuck jumps (Till & Cooke, 2009). Vest loading of 3-10% BM was used to increase the intensity of ballistic exercise by several authors and resulted in enhanced sprint performance 4-8 min after loaded single leg bounds (Turner et al., 2015) as well as 2-6 min after a loaded badminton-specific dynamic warm-up (Maloney et al., 2014), however, no change was reported when the time between a loaded dynamic warm-up and sprint performance was up to 17 minutes (Faigenbaum et al., 2006). Although APE/PAP is often studied by pairing biomechanically similar exercises, no studies to date have investigated the APE sprint response following ballistic exercise with lower body loading. The aim of this exploratory study was to determine the kinematic changes in sprint performance that occur after a range of ballistic exercise protocols with added lower body loading using a single subject research design (Backman et al., 1997).

Methods

One male rugby union athlete (former international representative) (29.2 years, 180.8 cm, 87.2 kg) completed four days of testing (Figure 13) each involving a standardised 20-minute warm-up followed by three maximal effort 40 m sprints (pre-test). All elements of warm-up and sprint testing were completed on an indoor running track. On days 1-3 the standardised warm-up was completed with no additional load, while on day 4 an additional load of 3% BM (i.e. 1.3 kg per leg) was attached to the lower body for the duration of the warm-up period. The WR was attached using a Lila™ Exogen™ compression-based exoskeleton suit (Sportboleh Sdh Bhd, Malaysia), with the load evenly distributed between the anterior and posterior aspects of the upper and lower leg (2/3 and 1/3 of the total added weight respectively) (Figure 14). After the three pre-test sprints on day 1-3, a short (<10 min) ballistic exercise protocol was completed prior to three post-test sprints. The ballistic exercise protocols involved: Day 1 = 3 x 5 double leg 45 cm drop jumps with 5% BM; Day 2 = 3 x 40 m loaded accelerations with 1-5% BM; Day 3 = 3 x 20 m flying sprints with 1% BM. Participants were asked to minimise CT and maximise FT when performing the drop jumps, and to sprint maximally during the loaded sprint interventions. The additional load was removed prior to all post-intervention sprint testing.

Split times for sprint performance (10, 30, 40, 10-30, 30-40 m) were recorded with photoelectic cells (Swift Speedlink, Swift Performance Equipment, Australia). Kinematic variables were recorded over the initial 15 m of each sprint with an Optojump system (Microgate, Italy; 1000 Hz) (Figure 15) and over the final 10 m of each sprint with high speed video (Sony RX 10, Sony, Japan; 300 Hz). The kinematic variables determined were FT, CT, SF, SL. Additionally kvert was determined from FT, CT and the BM of the subject (Morin et al., 2005). Each 40 m sprint was split into three phases: (i) the start phase (first 2 steps); (ii) the acceleration phase (steps 3-8); and, (iii) maximum velocity phase (four steps between the 30 and 40 m marks). Kinematic variables were averaged over the two to six steps in each phase.

The mean and SD for all three sprints during each set was calculated and analysed using a single subject AB research design (Backman et al., 1997). The mean and SD from the pre-test sets on days 1-3 provided a baseline for comparison. A substantial change was deemed to have occurred if set means after the loaded conditioning stimuli (i.e. drop jumps, loaded accelerations, flying sprints or loaded warm-up) fell outside a two SD band from the baseline mean value.

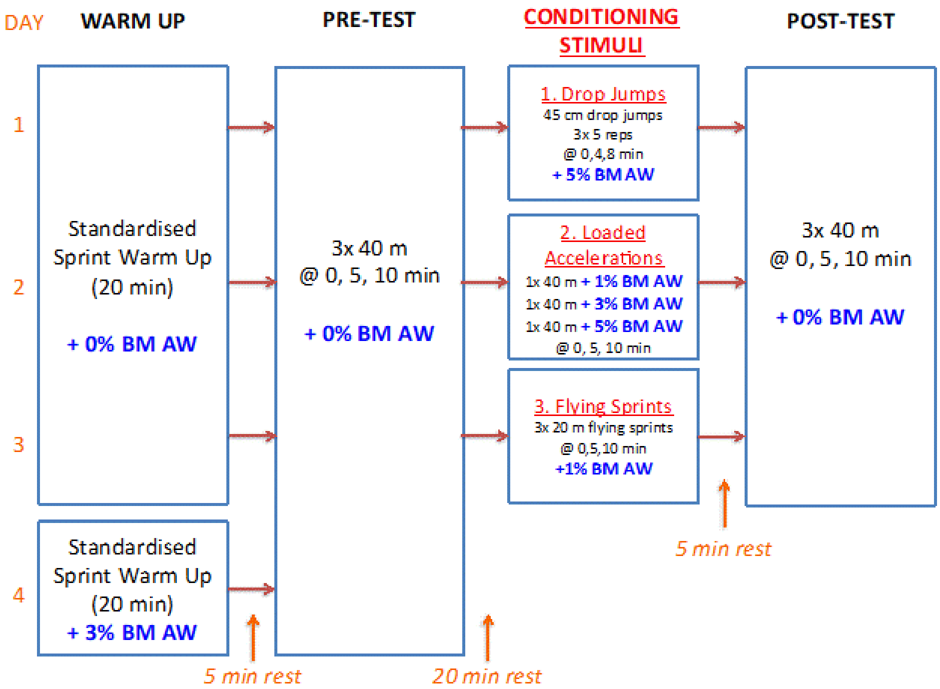

Figure 13. Testing protocols for Days 1-4.

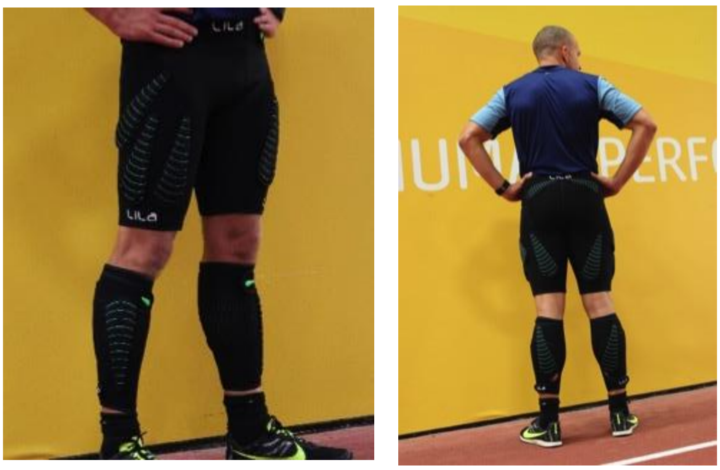

Figure 14. Exogen exoskeleton lower body loading with 1.3 kg attached to each leg (i.e. 3% BM).

Figure 15. Sprint test set-up including timing lights and Optojump equipment.

Results

The changes in sprint split times (Table 23) and sprint kinematics (Table 24) were compared to baseline results.

Drop Jumps: SL was reduced by up to 5% during the start and acceleration phases. The 40 m split time was 1% slower after the drop jumps and this was associated with a 5% decrease in vertical stiffness during the maximum velocity phase.

Loaded Accelerations: The 10 m split time was 3% faster after the loaded accelerations. CT was up to 3% longer during the start and acceleration phases and SF was 2% lower during the acceleration phase. FT was 3% longer and SF was 3% lower during the maximum velocity phase, however the 30-40 m split time was not substantially changed.

Flying Sprints: There was no substantial change in sprint performance at any distance after the flying sprints. CT was 3% longer during the start phase, while during the acceleration phase CT was longer (4%) and FT/CT ratio (-4%), vertical stiffness (-9%) and SF (-2%) were all lower. The only substantial change during the maximum velocity phase was a 2% reduction in SL.

Loaded Warm-Up: There was a substantial improvement in 10, 30 and 40 m split times of up to 4% after the loaded warm-up. CT was longer (4%) and the FT/CT ratio was lower (13%) during the start phase, while SF was slightly lower (1%) during the acceleration phase. The change in the 30-40 m time did not exceed the two SD threshold, but substantial changes in sprint kinematics were recorded during the maximum velocity phase: shorter CT (5%) and increased FT (2%), FT/CT ratio (7%), vertical stiffness (13%) and SF (1%).

Table 23. Mean ± SD for sprint split times up to 40 m after a standardised warm-up (baseline) or after a ballistic intervention. Changes of more than two SD from baseline are deemed substantial and are highlighted in bold.

	10 m (s)	**30 m (s)**	**40 m (s)**	**30-40 m (s)**
BASELINE	**1.87 ± 0.02**	**4.26 ± 0.03**	**5.38 ± 0.03**	**1.13 ± 0.02**
Drop Jumps	1.90 ± 0.09	4.31 ± 0.11	**5.45 ± 0.12**	1.14 ± 0.02
Loaded Accel.	**1.81 ± 0.06**	4.23 ± 0.07	5.38 ± 0.09	1.15 ± 0.03
Flying Sprints	1.89 ± 0.10	4.29 ± 0.08	5.44 ± 0.10	1.15 ± 0.02
Loaded Warm-Up	**1.80 ± 0.08**	**4.18 ± 0.08**	**5.30 ± 0.08**	1.12 ± 0.02

Discussion

The two ballistic exercise interventions that resulted in a substantial acute improvement in sprint performance were the loaded accelerations and the loaded warm-up protocol. Both protocols resulted in longer CT during the start and acceleration phases enabling more time for F_h application, lower SF during the acceleration phase and a performance improvement over the initial 10 m. However, it was only following the loaded warm-up that maximum velocity phase sprint kinematics were altered in a way that is consistent with improved maximum velocity phase performance (increased FT, SF and kvert and decreased CT), and that the speed improvement was sustained through to the end of the 40 m sprint. Conversely, loaded drop jumps with 5% BM altered performance in a way that resulted in decreased start and acceleration phase SL and a 5% decrease in maximum velocity phase kvert that was associated with an impairment in 40 m sprint performance.

Table 24. Mean ± SD for general sprint performance kinematic descriptors during the start, acceleration and maximum velocity phases. Changes of more than two SD from baseline were deemed substantial and are highlighted in bold.

		Start Phase	**Acceleration Phase**	**Maximum Velocity Phase**
Flight Time (s)	BASELINE	0.057 ± 0.003	0.085 ± 0.001	0.124 ± 0.004
	Drop Jumps	0.061 ± 0.001	0.084 ± 0.002	0.123 ± 0.003
	Loaded Accel.	0.056 ± 0.003	0.086 ± 0.002	**0.128 ± 0.008**
	Flying Sprints	0.057 ± 0.002	0.084 ± 0.001	0.124 ± 0.004
	Loaded Warm-Up	0.051 ± 0.006	0.084 ± 0.003	**0.126 ± 0.005**
Contact Time (s)	BASELINE	0.175 ± 0.002	0.142 ± 0.001	0.107 ± 0.001
	Drop Jumps	0.172 ± 0.005	0.142 ± 0.002	0.109 ± 0.003
	Loaded Accel.	**0.180 ± 0.007**	**0.145 ± 0.001**	0.109 ± 0.001
	Flying Sprints	**0.181 ± 0.005**	**0.148 ± 0.001**	0.108 ± 0.001
	Loaded Warm-Up	**0.182 ± 0.009**	0.144 ± 0.001	**0.102 ± 0.004**
Flight Time / Contact Time	BASELINE	0.325 ± 0.020	0.599 ± 0.008	1.16 ± 0.02
	Drop Jumps	0.357 ± 0.016	0.594 ± 0.010	1.12 ± 0.05
	Loaded Accel.	0.309 ± 0.007	0.593 ± 0.014	1.18 ± 0.07
	Flying Sprints	0.313 ± 0.016	**0.567 ± 0.006**	1.15 ± 0.04
	Loaded Warm-Up	**0.282 ± 0.044**	0.585 ± 0.025	**1.24 ± 0.09**
Vertical Stiffness (kN/m/kg)	BASELINE	0.20 ± 0.01	0.33 ± 0.01	0.63 ± 0.01
	Drop Jumps	0.21 ± 0.01	0.33 ± 0.01	**0.60 ± 0.04**
	Loaded Accel.	0.19 ± 0.01	0.31 ± 0.01	0.62 ± 0.02
	Flying Sprints	0.19 ± 0.01	**0.30 ± 0.01**	0.62 ± 0.01
	Loaded Warm-Up	0.19 ± 0.02	0.32 ± 0.01	**0.71 ± 0.06**
Step Length (m)	BASELINE	1.11 ± 0.02	1.56 ± 0.01	2.05 ± 0.03
	Drop Jumps	**1.06 ± 0.02**	**1.51 ± 0.02**	2.04 ± 0.02
	Loaded Accel.	1.13 ± 0.02	1.58 ± 0.01	2.06 ± 0.02
	Flying Sprints	1.11 ± 0.02	1.58 ± 0.01	**2.01 ± 0.01**
	Loaded Warm-Up	1.14 ± 0.02	1.56 ± 0.01	2.04 ± 0.02
Step Frequency (Hz)	BASELINE	4.32 ± 0.05	4.41 ± 0.01	4.34 ± 0.02
	Drop Jumps	4.30 ± 0.06	4.42 ± 0.06	4.31 ± 0.02
	Loaded Accel.	4.26 ± 0.20	**4.33 ± 0.04**	**4.23 ± 0.14**
	Flying Sprints	4.23 ± 0.09	**4.32 ± 0.02**	4.31 ± 0.02
	Loaded Warm-Up	4.30 ± 0.07	**4.38 ± 0.06**	**4.39 ± 0.05**

Rather than the simple interaction of potentiation and fatigue explaining the acute changes in sprint performance observed in the current study, an alternate proposition is motor pattern interference caused by the lower limb loading of the prior activity. The added lower body loads lowered the subject's centre of mass and likely kinesthetically reinforced the ideal leg "piston" sprint acceleration mechanics (providing strong negative feedback for letting the lower shank swing through) and perhaps encouraging a more horizontal GRF application, which is important for acceleration performance (Kugler & Janshen, 2010; Morin et al., 2011). Overloading the vertical force pattern with drop jumps and the more upright flying sprints likely had a reduced effect on the acceleration phase motor patterns and therefore did not result in a change in performance over this F_h dominant section.

Other authors have also reported acutely enhanced sprint performance after unilateral, cyclic ballistic exercise with added weight (Maloney et al., 2014; Till & Cooke, 2009), however the current study is the first to assess lower body loaded ballistic exercise as a conditioning stimulus for the acute enhancement of sprint performance and to include extensive general kinematic descriptors of performance (e.g. CT, FT, SL, SF). Light lower body loading of sprint accelerations appears to potentially provide a non-verbal cue for improved sprint acceleration mechanics. Further research is required to test the acute and chronic efficacy of this training method with a larger group of athletes, including a more precise delineation of the performance effects at multiple time points after the conditioning stimulus. Quantifying the changes in sprint kinetics as well as early acceleration phase sprint mechanics and considering the impact of subject strength level and muscle fibre type composition will also enhance the understanding of this topic.

Practical Applications

Added lower body loading equivalent to 3-5% BM worn during a dynamic speed warm-up or a series of 40 m sprint accelerations appears to be effective at acutely improving sprint acceleration performance. Rather than loaded bilateral, acyclic drop jumps, loading the sprint acceleration cycle directly is more effective at eliciting an acute enhancement in performance, perhaps due to the positive stimulus for lower limb acceleration mechanics provided by the lower body loading. Further research is required to determine if the performance changes include a PAP effect or are entirely motor pattern modification, and how this effect may differ with trained sprinters.

SECTION 4

CHRONIC CHANGES IN SPRINT-RUNNING PERFORMANCE WITH WEARABLE RESISTANCE TRAINING

CHAPTER 11

CHANGES IN SPRINT-RUNNING PERFORMANCE FOLLOWING SIX WEEKS OF LOWER BODY WEARABLE RESISTANCE TRAINING

This paper comprises the following paper prepared for *European Journal of Sport Science*:

Simperingham, K. D., Cronin, J. B., Ross, A., Brown, S. R. & Macadam, P. (2019). Changes in sprint performance following six weeks of lower body wearable resistance training. *European Journal of Sport Science [In preparation]*.

Prelude

Two forms of contrast loading with lower body WR were identified in Chapter 10 that may result in a positive APE of subsequent sprint performance. Wearing WR during either a dynamic warm-up or a series of sprints resulted in a substantial increase in sprint performance 5 to 15 minutes later. The evidence provided by a single subject research design is somewhat limited, but the findings provide direction for future research and for further experimentation with WR training interventions. The four cross-sectional studies included in the previous section identified a range of significant changes in sprint performance and sprint biomechanics during sprints with lower body WR or within several minutes of removing the external load. The important next step is to implement a longitudinal training study to assess the chronic impact of overloading the sprint cycle with lower body WR for a period of several weeks. This chapter involved implementing a speed training program for a group of team sport athletes with half of the participants completing the training while wearing lower body WR, and half of the participants completing the same training without WR. The aim of the study was to quantify the changes in sprint performance and hip strength after a speed training intervention and to compare the effects with or without WR.

Introduction

Optimised acceleration, deceleration and maximum velocity sprint-running capacities are crucial for athletes to be successful in a range of team sports (e.g. rugby, American football and soccer), due to the frequent occurrence and anecdotally influential nature of short sprint efforts during games (Gabbett, 2012; Lindsay et al., 2015; Ross et al., 2015; Spencer et al., 2005; Vigne et al., 2010). Diverse sprint training techniques remain an area of intense research interest (Kawamori, Newton, et al., 2013; Lockie et al., 2014; Lockie et al., 2012), but substantial conjecture surrounds the ideal training methods (Bolger et al., 2015; Rumpf et al., 2016). Resisted sprint training is classified as a specific strength training method and is thought to optimise the transference of any adaptation to sprint performance given the biomechanical similarity of the exercise stimulus. One such resisted technique is WR training, which involves completing sporting movements with added weight attached directly to the body (Macadam, Cronin, et al., 2017). Based mainly on acute observational studies, WR was proposed as a method that can provide specific overload to sprinting (Dolcetti et al., 2018; Macadam, Simperingham, & Cronin, 2017; Simperingham & Cronin, 2014), and therefore potentially chronic benefits to sprint performance when applied over a period of training.

The specific overload provided by lower body WR and the differential impact of lower body compared to upper body WR during sporting movements (Couture et al., 2018; Macadam, Simperingham, Cronin, et al., 2017; Simperingham & Cronin, 2014) has led to recent research focus on lower body WR during sprinting (Feser et al., 2018; Macadam, Simperingham, & Cronin, 2017; Simperingham & Cronin, 2014). Sprinting speed during the first 10 m of acceleration was not changed while wearing lower body WR of up to 5% BM, but sprinting speed was significantly lower after 10 m (Macadam, Simperingham, & Cronin, 2017; Simperingham & Cronin, 2014). The pattern of longer ground CT and lower SF with lower body WR was similar between the acceleration phase and maximum velocity phase (Feser et al., 2018; Hurst et al., 2018; Macadam, Simperingham, & Cronin, 2017; Simperingham, Cronin, Pearson, & Ross, 2016; Simperingham & Cronin, 2014). There is some evidence that moderate lower body WR (3% BM) may provide a stimulus to increase F_h output during the acceleration phase of sprinting (Simperingham, Cronin, Pearson, et al., 2016) and a stimulus that may chronically increase vertical stiffness during the maximum velocity phase (*unpublished findings*, Chapter 9).

In addition to overloading several mechanical determinants of sprint performance (e.g. CT and SF), lower body WR can theoretically improve the effectiveness of sprint training programs by specifically overloading the hip flexors and by taking advantage of potential within-session acute enhancement of sprint performance by using contrast loading protocols (Simperingham et al., 2015). Hip flexor moment is related to sprint velocity (r = 0.69) (Ema et al., 2018), so sprint training with lower body WR may prove effective due to the additional muscular work required to counteract the added rotational inertia of the legs compared to during unloaded sprinting. Ballistic exercise can augment subsequent power performance (Maloney et al., 2014), and there is some evidence of acutely improved sprint performance following unloaded and upper body loaded bounding (Turner et al., 2015), and after lower body loaded sprints and after an entire warm-up with lower body WR (Simperingham et al., 2015). Several studies also reported no change in sprint performance following an upper body loaded warm-up (Faigenbaum et al., 2006), so more research is required in this area. Given there is no evidence of a decrement in sprint performance with contrast WR loading, this technique could be safely incorporated into WR training programs.

Early studies of WR training included reports of significantly increased vertical jump performance in well trained track and field athletes after wearing weighted vests (11 to 13% of BM) throughout the day for three weeks, however changes in sprinting speed were not reported (Bosco, 1985; Bosco et al., 1986). When equivalently loaded vests were worn for eight days, sprinting speed was not significantly altered within a group of rugby players (Barr et al., 2015). The longitudinal effects of lower body WR have not been thoroughly researched, but Pajic (2011) reported no change in maximum running speed after six weeks of up to 15 repetitions of 50 m sprints with 2.5% BM load attached to each ankle. Additional training studies using lower body WR are required to better understand the chronic effects on sprint performance of training with WR.

The aim of this study was to quantify the changes in sprint performance and hip flexor/extensor strength after implementing a sprint training program incorporating lower body WR with a group of team sport athletes. It was hypothesised that after six weeks of training, peak hip flexor torque and sprint performance would improve more in the WR training group compared to the control group.

Methods

Participants

Twenty-six male rugby players initially volunteered to take part in the training study. Three subjects withdrew due to injury (n = 2; unrelated to the training study), and selection into a representative training squad (n = 1), leaving a final sample of 23 male rugby union athletes (18.4 ± 0.4 years; 180.2 ± 8.4 cm; 96.5 ± 16.4 kg). All participants were currently active with pre-season rugby training, but otherwise were following no structured, supervised training program. Participants had no previous experience with sprint training with WR. Approval for the study was obtained from the institutional research ethics committee and participants provided written informed consent prior to participating in the study.

Training Procedures

Participants committed to completing two supervised 60 min speed training sessions each week for six weeks. Participants were randomly allocated into the experimental (WR) group (n = 13) or the control group (n = 10). The details of the training program are included in Table 25 and Table 26. All participants completed the same sessions, except the experimental group wore Lila™ Exogen™ compression shorts and calf sleeves (Sportboleh Sdh Bhd, Malaysia) throughout the sessions (Figure 16). WR group participants started every session with between 3% BM and 5% BM of WR attached with Velcro to the legs. Approximately two-thirds of the weight was attached to the thighs (half on the anterior aspect and half on the posterior aspect), and approximately one-third of the weight attached to the shanks (also with half on the anterior aspect and half on the posterior aspect). The magnitude of WR was gradually increased over the 6 weeks (week 1: 3% BM; week 6: 5% BM). Proximal loading configurations were progressed to distal loading configurations (Figure 17) of the same magnitude to gradually increase the impact of the WR (Dolcetti et al., 2018). The added loads were completely removed, or reduced to 1% BM loading at a certain point during 10 of the 12 sessions, in order to manage the progression of loading over time and also in an attempt to take advantage of a potential APE of power performance with contrast loading (Simperingham et al., 2015).

The session focus was mainly sprint starts and the acceleration phase during the initial three weeks (Table 25). More focus on the maximum velocity phase was included during weeks four to six (Table 26). The total sprint distance was 100 m during the first session and progressed up to a maximum of 300-320 m during the final three training sessions. The total number of jumps per session increased from 8-10 in week one, to a maximum of 75 in week five.

Figure 16. Sprint training session including both WR group (wearing lower body WR) and control group (no WR) participants.

Figure 17. Lower body WR: distal (left-hand image) and proximal (right-hand image) loading configurations of equivalent magnitudes (0.2 kg on the anterior aspect of each leg).

Table 25. Sprint training program: Weeks 1-3.

		WEEK 1				**WEEK 2**				**WEEK 3**			
		Focus: Starts, 0-10m, start/acceleration technique				***Focus: Accel, 0-20m, acceleration technique***				***Focus: 0-30m, acceleration + maximum velocity technique***			
		SESSION 1.1		**SESSION 1.2**		**SESSION 2.1**		**SESSION 2.2**		**SESSION 3.1**		**SESSION 3.2**	
		LOAD	**DRILLS**	**LOAD**	**DRILLS**	**LOAD**	**DRILLS**	**LOAD**	**DRILLS**	**LOAD**	**DRILLS**	**LOAD**	**DRILLS**
1	**GENERAL WARM-UP**	**3% BM proximal**	60m: Jog x2 Side (20+20m) + Jog x2 Butt Kicks (20m) + Jog x2 Carioca (20+20m) + Jog x2	**3% BM proximal**	60m: Jog x2 Side (20+20m) + Jog x2 Butt Kicks (20m) + Jog x2 Carioca (20+20m) + Jog x2	**3% BM proximal**	10m drill + 10m accel x2: Jog, Ankling, Side, High Knees, Carioca, Butt kicks	**3% BM proximal**	10m drill + 10m accel x2: Jog, Ankling, Side, High Knees, Carioca, Butt kicks	**3% BM distal**	10m drill + 10m accel x2: Jog, Ankling, Side, High Knees, Carioca, Butt kicks	**3% BM distal**	10m drill + 10m accel x2: Jog, Ankling, Side, High Knees, Carioca, Butt kicks
2	**DYNAMIC STRETCH 1**	**3% BM proximal**	Calf Pumps x10E Sumo Squat x8 Standing Back Twist x10E Traveling Lunge + Twist (frontal) x8E Walking Quad x8E Walking Knee-to-chest x8E	**3% BM proximal**	Calf Pumps x10E Sumo Squat x8 Standing Back Twist x10E Traveling Lunge + Twist (frontal) x8E Walking Quad x8E Walking Knee-to-chest x8E	**3% BM proximal**	Seated routine: Seated twist x5E, Leg swings/scissors x10E Lunge x10E	**3% BM proximal**	Walking: Lunge/twist x6E, Quad x8E, Knee up - plantar flex x8E, Hurdler fwd/back x8E, Leg swing x10E, Calf pumps x10E	**3% BM distal**	MD Lunge (forward/side/back) x3E Toe taps x8E	**3% BM distal**	MD Lunge (forward/side/back) x3E Toe taps x8E
3	**POWER: SPEED/ PREPERATION DRILLS**	**3% BM proximal**	Arms standing 10s x2, seated 10s x2 <u>Accel Wall Drills:</u> posture hold 45 degree 10s x2; Marching 5E leg x2, Single leg exchange 5E x2; Double leg exchange right x5, left x5 Accel March (static x5s + walking x5m) x2 Accel Skip (static x5s + walking x5m) x2	**3% BM proximal**	Arms standing 10s x2, seated 10s x2 <u>Accel Wall Drills:</u> Load & lift x5E x2 Marching 5E leg x2, Single leg exchange 5E x1; Double leg exchange right x5, left x5 Triple leg exchange x10 Accel March (static x5s + walking x5m) x2 Accel Skip (static x5s + walking x5m) x2	**3% BM proximal**	Arms standing 10s x2, seated 10s x2 <u>Accel Wall Drills:</u> Marching 5E leg x2, Load & lift x5E Double leg exchange right x5, left x5 Accel March (static x5s + walking x5m) x2 Accel Skip (static x5s + walking x5m) x2	**3% BM proximal**	Arms standing 10s x2, seated 10s x2 <u>Accel Wall Drills:</u> Load & lift x5E x2 Marching 5E leg x2, Single leg exchange 5E x1; Double leg exchange right x5, left x5 Triple leg exchange x10 Accel March (static x5s + walking x5m) x2 Accel Skip (static x5s + walking x5m) x2	**3% BM distal**	Overhead Accel March (static x5s + walking x5m) x2 Overhead Accel Skip (static x5s + walking x5m) x2 Ankle runs 10mx2 Shin runs 10mx2 Knee runs 10mx2	**3% BM distal**	Overhead Accel March (static x5s + walking x5m) x2 Overhead Accel Skip (static x5s + walking x5m) x2 Ankle runs 10mx2 Shin runs 10mx2 Knee runs 10mx2
4	**DYNAMIC STRETCH 2**	**3% BM proximal**	Traveling Lunge + Twist (transverse) x6E Side Lunge x6E CMJ x5	**3% BM proximal**	Traveling Lunge + Twist (transverse) x6E Side Lunge x6E CMJ x5	**3% BM proximal**	Traveling Lunge + Twist (transverse) x6E Side Lunge x6E CMJ x5	**3% BM proximal**	Sumo squat x10 Lat leg swing x10E	**3% BM distal**	Traveling Lunge + Twist (transverse) x6E Side Lunge x6E CMJ x5	**3% BM distal**	Sumo squat x10 Lat leg swing x10E
5	**ACTIVATION DRILLS/ PLYOMETRICS 1**	**3% BM proximal**	Broad jumps x5 x2 sets	**3% BM proximal**	10m acceleration x3 (70,80,90%)	**3% BM proximal**	10m acceleration x3 (70,80,90%)	**3% BM proximal**	10m acceleration x3 (70,80,90%)	**3% BM distal**	Skip x1min 30m form sprint @80% x1 Skip x1min 30m form sprint @80% x1	**3% BM distal**	Skip x1min 30m form sprint @80% x1 Skip x1min 30m form sprint @80% x1
6	**SPRINTS**	**0% BM**	Partner lean starts - 10m x5 x1 set 10 m sprints x5 x1 set (standing start)	**0% BM**	Partner lean starts - 10m x5 x1 set 10 m sprints x5 x1 set (standing start) 10m get ups x4 x1 set (press up, facing back, press up, 1 knee)	**3% BM proximal**	10m x4 20m x4 20m x4 - Get Ups	**3% BM** **3% BM** **0% BM**	10m x4 20m x4 20m x4 - Get Ups (no race rep 1; then race in positional groups)	**3% BM distal**	10, 10, 20, 20, 30 m x1 30, 20, 20, 10, 10m x1	**3% BM distal**	10, 10, 20, 20, 30 m x1 30, 20, 20, 10, 10m x1 30m x1
7	**PLYOMETRICS 2**	**0% BM**	N/A	**0% BM**	Broad jumps x4 (i.e. 2+2) x2 sets	**0% BM**	Broad jumps x4 (i.e. 2+2) x3 sets	**0% BM**	Broad jumps x4 (i.e. 2+2) x3 sets	**3% BM distal**	Broad jump x5 (continuous) x3 Single leg hop x10E x2	**3% BM distal**	Broad jump x5 (continuous) x3 Single leg hop x10E x2
	Total Sprint Distance (m)	**100**		**140**		**200**		**200**		**180**		**210**	
	Total Jumps (#)	**10**		**8**		**12**		**12**		**55**		**55**	

Table 26. Sprint training program: Weeks 4-6.

		WEEK 4				WEEK 5				WEEK 6			
		Focus: 0-30m, acceleration + maximum velocity technique				*Focus: 0-40m, maximum velocity*				*Focus: 0-50m, acceleration + maximum velocity*			
		SESSION 4.1		SESSION 4.2		SESSION 5.1		SESSION 5.2		SESSION 6.1		SESSION 6.2	
		LOAD	DRILLS	LOAD	DRILLS	LOAD	DRILLS	LOAD	DRILLS	LOAD	DRILLS	LOAD	DRILLS
1	GENERAL WARM-UP	4% BM proximal	60m: Jog x2 Butt Kicks (20m) + Jog 20m + Butt kicks 20m x2 Carioca (20+20m) + Jog x2	4% BM proximal	10m drill + 10m accel x2: Jog, Ankling, Side, High Knees, Carioca	4% BM proximal	10m drill + 10m accel x2: Jog, Ankling, Side, High Knees, Carioca	4% BM proximal	10m drill + 10m accel x2: Jog, Low knee (fast feet), High Knees, Carioca	5% BM proximal	10m drill + 10m accel x2: Jog, Ankling, Low knees	5% BM distal	10m drill + 10m accel x2: Jog, Ankling, Low knees, High knees
2	DYNAMIC STRETCH 1	4% BM proximal	MD Lunge x3E Inchworm x4 Press up - foot to hand x5E Standing back twist x5E Standing leg swings x10E	4% BM proximal	MD Lunge x3E Inchworm x4 Press up - foot to hand x5E Standing back twist x5E Standing leg swings x10E	4% BM proximal	MD Lunge x3E Inchworm x4 Seated back twist x5E	4% BM proximal	MD Lunge x3E Sumo SQ x8 Standing twist x5E Calf pumps x10E Fott to hand x5E Standing leg swings x10E	5% BM proximal	Lunge + twist x5E Walking quad x8E Walking knee to chest x8E Walking hurdler forward/back x5E Walking toe taps	5% BM distal	Lunge + twist x5E Walking quad x8E Walking knee to chest x8E Walking hurdler forward/back x5E Walking toe taps
3	POWER: SPEED/ PREPERATION DRILLS	4% BM proximal	Vmax wall drills: - Down-back-up x2 - Single leg cycles x2E Ankle skip 15m x2 Ankle bound 15m x2	4% BM proximal	Overhead Accel March (static x5s + walking x5m) x2 Overhead Accel Skip (static x5s + walking x5m) x2	4% BM proximal	OH Accel March 15m x2 OH Accel Skip 15m x2 Ankle skip 15mx2 Ankle bound 15mx2	4% BM proximal	OH Accel Skip 20m x3	5% BM proximal	Accel March 15m x2 (not OH) Accel skip 15m x2 (not OH) Straight leg skip (force focus) 20m x2 Straight leg shuffle (SF focus) 20m x2 OH Ankle runs 1x10m OH Shin runs 1x10m OH Ankle/shin/knee runs 5/5/10m x3	5% BM distal	Overhead Accel March 15mx2 Overhead Accel Skip 15mx2 Straight leg skip (force focus) 20m x2 Straight leg shuffle (SF focus) 20m x2 OH Ankle runs 1x10m OH Shin runs 1x10m OH Ankle/shin/knee runs 5/5/10m x3
4	DYNAMIC STRETCH 2	4% BM proximal	Lateral leg swing x10E Walking squat and twist x5E	4% BM proximal	Lateral leg swing x10E Walking squat and twist x5E	4% BM proximal	Traveling Lunge + Twist (transverse) x6E Standing straight leg swings x8E	4% BM proximal	Arm drills	5% BM proximal	Straight leg swings x10E Lat leg swings x5E Walking squat and twist x5E	5% BM distal	Straight leg swings x10E Lat leg swings x5E Walking squat and twist x5E
5	ACTIVATION DRILLS/ PLYOMETRICS 1	4% BM proximal	Straight leg skip (force focus) 15m x2 Straight leg shuffle (SF focus) 15m x2 Skip x1min 30m form sprint @80% x1 Skip x1min 30m form sprint @80% x1	0% BM	Straight leg skip (force focus) 15m x2 Straight leg shuffle (SF focus) 15m x2 Ankle runs 10mx1, Shin runs 10mx1 Knee runs 10mx2 Skip x1min, 30m form sprint @80% x1 Skip x1min, 30m form sprint @80% x1	1% BM proximal	Straight leg skip (force focus) 15m x2 Straight leg shuffle (SF focus) 15m x2 Ankle-shin-knee runs (5/5/10m) x4 [40m accel's over low hurdles]: Skip x1min, 40m form sprint @80% x1 Skip x1min, 40m form sprint @80% x1	1% BM proximal	Straight leg skip (force focus) 20m x2 Straight leg shuffle (SF focus) 20m x2 Ankle-shin-knee runs (5/5/10m) x4	5% BM proximal	Pogos x5 x2 Broad jump x5 (continuous) x2 Warm up form sprints 40m x2	5% BM distal	Pogos x5 x2 Broad jump x5 (continuous) x2
6	SPRINTS	4% BM 0% BM	10/10/10m x4 (100/75/100%) Ins & Outs 30m x4	4% BM 0% BM	10/10/10m x5 (100,75/100%) Ins & Outs 30m x4	1% BM proximal	20/20m x4 rolling start/100% (sprints over cones set at 1.75-1.9 and 1.8-2m - 2 different distances based on step length or height) 40m x3	1% BM proximal	20/10/10m x4 Ins&Outs 40m x3	5% BM 0% BM	40,30,20,10m x1 20/30m x4 rolling start/100%	5% BM 0% BM	10,10,20,30,20,10,10 x1 20/10/20m x4 [Complete at the end, after Plyometrics 2]
7	PLYOMETRICS 2	0% BM	2 Leg high hurdle jumps x5 x3sets Alternate leg bounding x10E x2	0% BM	2 Leg high hurdle jumps x5 x3sets Alternate leg bounding x10E x2	1% BM proximal	2 Leg high hurdle jumps x5 x3sets Alternate leg bounding x10E x3	1% BM proximal	2 Leg high hurdle jumps x5 x3sets Alternate leg bounding x10E x3	0% BM	2 Leg high hurdle jumps x5 x3sets Alternate leg bounding x10E x2	5% BM distal	2 Leg high hurdle jumps x5 x3sets Alternate leg bounding x10E x3
	Total Sprint Distance (m)	240		270		280		320		300		310	
	Total Jumps (#)	55		55		75		75		65		60	

Testing Procedures

Participants completed the same battery of tests two weeks before and two weeks after the six-week training period. Sprint performance over 40 m was assessed on an indoor track. Isokinetic hip strength on an isokinetic dynamometer and maximum power output during a cycle-based sprint test were both assessed in a controlled laboratory setting.

Prior to the warm-up participants put on Exogen™ pants and calf sleeves and wore them throughout the speed testing session. Height and body mass were recorded without shoes. A 20-minute standardised warm-up was completed on an indoor track (including jogging, sprint drills, dynamic stretching and build-up sprints of increasing intensity up to maximal effort). After the warm-up there was a period of five minutes of passive rest to ensure full recovery. Participants completed the sprint, isokinetic hip strength and cycling power assessments in a randomised order, always with five minutes of passive rest prior to each test. Participants were requested to not complete any high intensity training in the 24 hours prior to testing sessions and to present to the testing session well hydrated and having not eaten at least 90 minutes prior to the start of testing.

Data Collection and Processing

Instantaneous horizontal velocity was measured continuously with a radar device (Stalker ATS II, Texas, USA; 47 Hz), which was connected to a laptop running Stalker ATS System™ software (Version 5.0.2.1, Applied Concepts, Inc., Texas, USA) for data acquisition. The radar was positioned 10 m directly behind the sprint start position on a tripod set at a vertical height of 1 m to approximately align with the centre of mass of the sprinting subjects (Morin et al., 2006). The data file for each trial together with the height and body mass of each participant was imported into a custom-made LabVIEW (Version 13.0, National Instruments Corporation, Texas, USA) program that was used to calculate outcome variables consistent with procedures previously reported (Cross et al., 2015; Simperingham et al., 2019). Outcome variables included: F0; Pmax, S_{Fv} and split times for distances between 5 and 40 m. "Functional" values for F0, Pmax and S_{Fv} were calculated by dividing by BM.

Maximum velocity (vmax) was determined as the peak speed achieved during the 40 m sprint. The velocity-time curve [v(t)] for each sprint was fitted to an exponential function:

$$v(t) = vmax * (1 - e^{-t/\tau})$$

Where t is the time and τ is the time constant. Instantaneous horizontal acceleration was calculated as the first derivative of the equation above and used to calculate F_h from Newton's second law of motion:

$$F_h(t) = [m * a(t)] + F_{air}(t)$$

Where m is the body mass of the subject plus added WR and F_{air} is the air friction during sprinting, which is influenced by the frontal area of the subject (*Af*) (Arsac & Locatelli, 2002).

$$Af = (0.2025 * height^{0.725} * m^{0.425}) * 0.266$$

F0 and V0 were determined as the y-axis and x-axis intercepts of the force-velocity curve and were used to calculate Pmax and S_{Fv}:

$$Pmax = (0.5*F0) * (0.5*V0)$$

$$S_{Fv} = - F0_{rel} / V0$$

An Optojump system (Microgate, Italy; 1000 Hz) was positioned over the initial 15 m of each sprint and was used to determine the FT, CT, SL, SF of each step (Macadam, Simperingham, & Cronin, 2017). The bars were positioned in parallel on either side of the running lane and the duration of interruptions in communication between the bars was monitored to calculate the kinematic variables of interest. Sprint accelerations were split into the start phase (first 2 steps) and the acceleration phase (steps 3-8). Dependent variables were averaged over the two or six steps in each phase.

The 30 m to 40 m section of the sprint was recorded with high speed video (Sony RX 10, Sony, Japan; 300 Hz) using a camera positioned perpendicular to the 35 m mark on the track, at a distance of 10 m from the middle of the track. This section of the sprint was representative of the maximum velocity phase. Video files were manually analysed by one researcher to identify the timing of touchdown and toe-off for two steps per leg. This information together with the 30 to

40 m split time was used to calculate FT, CT, SF and SL. Kvert was determined based on the spring-mass paradigm using CT, FT and the BM of each participant (Macadam, Simperingham, & Cronin, 2017; Morin et al., 2005):

$kvert = Fmax/\Delta y$

Where $Fmax$ is the maximum vertical GRF during contact (in kN) and Δy is the vertical displacement (in m) of the centre of mass when it reaches its lowest point:

$Fmax = BM*g\pi/2(FT/CT+1)$

$\Delta y = Fmax*CT^2/BM\pi^2 + gCT^2/8$

Where g is the acceleration constant due to gravity. Effective kvert was calculated relative to total system mass (including the added WR). A four-step average was determined from each sprint for each of the video-derived variables.

Concentric hip strength was measured with a Humac Norm dynamometer (Lumex, Ronkonkoma, NY, USA) with participants lying in a supine position. A standardised protocol was used (Brown, Brughelli, & Bridgeman, 2016; Brown, Brughelli, Griffiths, & Cronin, 2014) to assess hip flexor and hip extensor peak torque at fixed speeds of 60°/s and 180°/s. Testing occurred through a limited 90° range of motion from full anatomical extension, to 90° of hip flexion on the right leg only. After the upper body was firmly secured in the dynamometer, participants completed three 60°/s familiarisation sets of three repetitions of hip flexion and extension. Familiarisation sets steadily increased in intensity from approximately 50% of maximum exertion in the first set, to 90% in the final set, with 45 s of rest between sets. After a two-minute rest, participants were instructed to complete one set of five repetitions at maximal intensity (60°/s). Three familiarisation sets were then completed at 180°/s, again at approximately 50%, 70% and 90% of maximum exertion. Following a two-minute rest a final set of five repetitions with maximal intensity was recorded at 180°/s.

The torque-angle curve was fitted with a fourth-order polynomial using a custom-made LabVIEW program (Version 14.0, National Instruments Corp, Austin, TX, USA). Peak torque (flexion and extension) was determined for each repetition and the average peak torque from repetitions 2-5 was used as the final value at each speed.

A custom-made inertial load (IL) cycle ergometer (High Performance Sport New Zealand, Auckland, NZ) was used to assess peak power output and the pedalling rate at peak power (optimal cadence) during a 4 s maximal effort cycling sprint. Inertial load cycle ergometers enable the torque-velocity relationship to be established from one short maximal sprint (Martin et al., 1997) by applying Newton's second law of rotation (net external torque = moment of inertia x angular acceleration). Combining a high cycle flywheel inertia and a high gear ratio means that the torque-velocity relationship is derived from a wide range of torque and angular velocity data within one short sprint effort. Participants started from a stationary position with the cranks aligned at an angle of 50° to the vertical and accelerated maximally for eight complete crank revolutions. Seat height and handlebar height was adjusted for each participant and the same settings were used for pre- and post-testing.

An optical sensor was used to measure the angular velocity (ω) of the flywheel every 10° of flywheel rotation. A custom LabVIEW program (National Instruments Corporation, Texas, USA) was used for data acquisition and post processing occurred in a custom spreadsheet. An overall gear ratio (G) of 4.77 (62:13) was used, so angular velocity of the crank was sampled every 2.1° of pedal crank rotation. The moment of inertia (I) of the flywheel was calculated to be 1.08 kgm^2 based on the method described by Crede (1948). Angular acceleration (α) was calculated as the time integral of the ω results. Instantaneous torque (T_I) and instantaneous power (P_I) were then calculated from the following equations:

$$T_I = \alpha IG$$

$$P_I = \alpha\omega I$$

Power was averaged over each complete crank revolution and the peak value for revolution averaged power output was used as the peak power output (PP_{IL}). Power output vs pedaling rate was fitted to a curve using the least squares method and the pedaling rate at PP_{IL} was identified as the optimal cadence in revolutions per minute.

The reliability, mechanical validity and concurrent validity of the IL technique was established previously (del Coso & Mora-Rodríguez, 2006; Martin et al., 1997). Cycle-trained subjects provided valid and reliable results from the first session of IL testing, but active men required at least two familiarisation sessions to achieve reliable power output results (Martin, Diedrich, & Coyle, 2000). The total volume of maximal effort cycling during each session was ≤ 16 s. Given the participants in the current study regularly completed cycle interval training, one extended familiarisation session was completed.

Statistical Analyses

The mean and SD for all dependent variables was calculated for each set of two sprints before (pre) and after (post) the six-week training intervention. Glass's delta effect sizes (ES) were calculated for pre-post comparisons for each dependent variable and the inferences associated with the effects were classified as trivial (0-0.19), small (0.20-0.59), moderate (0.60-1.19), and large (1.20-1.90) (Hopkins et al., 2009). Significant differences between the effects of the control and intervention training groups were evaluated using linear regression models, wherein each β value represents the mean difference between the control and intervention groups. Each outcome post-intervention was evaluated controlling baseline values. Values for β were only reported in the results when a statistically significant difference between the training groups was identified. Statistical significance was set at $p \leq 0.05$.

Results

The average of all radar-derived values are summarised in Table 27. For most speed variables there was a small effect towards improved speed from the six-week training intervention, but no significant difference between the control and WR training groups. All ES tended to be greater for the control group than the WR intervention group. The small improvement in 10 m to 35 m split times in the control group (-2.0 to -2.9%, ES = -0.38 to -0.53) was also evident in the WR group at 10 m (-1.6%, ES = -0.27), but the changes were only trivial at distances of 20 m and above (ES < 0.20). There was a small increase (3.8-8.1%, ES = 0.24-0.49) in F0 in both training groups and a small shift in S_{Fv} (4.8-7.0%, ES = -0.27 to -0.39) towards a more force-oriented force-velocity profile. There was also a small increase in Pmax but in the control group only. V0 changes were trivial in both groups, but the ES were in opposite directions (control ES = 0.18; WR group ES = -0.15). Maximum velocity was quantified more directly with the 25 to 35 m split time, which also had trivial ES, but no evidence of a decrement in performance for either group. The 25-35 m split time was used to represent the maximum velocity phase instead of the 30-40 m split time due to the radar velocity-time curve for some participants starting to decline prior to the 40 m mark. Following radar analysis protocols, the velocity-time curve was trimmed prior to deceleration so accurate 40 m split times could not be calculated for some individuals.

Pre- to post-training intervention changes in mean sprint kinematics were summarised in the three distinct sprint phases (Table 28):

Start Phase: There was a small decrease in CT (-1.4%, ES = -0.33) and a small increase in SF (2.3%, ES = 0.34) in the control group, but all changes in the intervention group were trivial (ES ≤ 0.20).

Acceleration Phase: After the training intervention there was a moderate decrease in CT (-3.3 to -3.6%, ES = -0.64 to -0.73) and increase in vertical stiffness (7.4-8.2%, ES = 0.60-0.74) in both training groups. The only significantly different training response between the control and WR groups occurred in the acceleration phase. There was a small increase in FT after training with WR (8.9%, ES = 0.45), while FT was unchanged in the control group (ES < 0.20). The β value from the linear regression was 0.007 s (95% confidence interval = 0.001-0.012 s; t = 2.42, p = 0.025), indicating that mean post-intervention difference in FT between the control and intervention groups was 0.007 s. There was a small increase in SF in the control group (2.4%, ES = 0.43), while SF was unchanged in the WR group (ES < 0.20). The β value from the linear regression was -0.14 Hz (95% confidence interval = -0.01 to -0.28 Hz; t = -2.23, p = 0.037), indicating that mean post-intervention difference in acceleration phase SF between the control and intervention groups was -0.14 Hz.

Maximum Velocity Phase: Regardless of training group, after the training intervention there was a small decrease in CT (-1.9 to -2.3%, ES = -0.20 to -0.22) and a small increase in both SF (1.5%, ES = 0.29; control group only) and vertical stiffness (4.7-6.0%, ES = 0.20-22).

Post-training ES were trivial to moderate for hip flexion and hip extension peak torque across the control and WR intervention groups (

Table 29). The magnitude of the changes tended to be larger at the faster testing speed (180°/s; ES = 0.43-0.87), but there was no significant difference between the responses of the two groups. Control group hip flexion and hip extension peak torque increased by 3.5-6.6% (ES = 0.25-0.52), while the intervention group peak torque changes (2.6-11.0%) ranged from trivial (hip flexion peak torque at 60°/s ES = 0.17) to moderate (hip extension peak torque at 180°/s ES = 0.87).

There was a small increase in PP_{IL} during the inertial load cycle ergometer test only in the control group (3.4%, ES = 0.40) (

Table 29). There was no substantial change in optimal cadence after the training intervention.

Attendance at planned training sessions was inconsistent, with the WR group participants completing on average 10 of the 12 planned training sessions, while the control group participants completed on average 9 of the 12 planned training sessions. Five participants in each group completed less than 80% of the planned training sessions. The missed training sessions were not replaced.

Table 27. Radar derived values (mean ± SD) quantifying 40 m sprint performance before and after a six-week training intervention.

	Control Group			WR Intervention Group		
	Pre	**Post**	**ES**	**Pre**	**Post**	**ES**
10 m (s)	2.18 ± 0.08	2.11 ± 0.11	-0.53	2.13 ± 0.15	2.10 ± 0.10	-0.27
20 m (s)	3.54 ± 0.13	3.46 ± 0.17	-0.43	3.44 ± 0.20	3.41 ± 0.14	-0.18
30 m (s)	4.80 ± 0.18	4.71 ± 0.23	-0.39	4.66 ± 0.27	4.63 ± 0.20	-0.12
35 m (s)	5.43 ± 0.21	5.32 ± 0.28	-0.38	5.26 ± 0.31	5.24 ± 0.22	-0.10
25-35 m (s)	1.26 ± 0.06	1.23 ± 0.06	-0.29	1.21 ± 0.08	1.21 ± 0.06	0.03
V0 (m/s)	8.23 ± 0.43	8.33 ± 0.44	0.18	8.61 ± 0.62	8.53 ± 0.49	-0.15
F0 (N/kg)	7.54 ± 0.65	8.15 ± 0.80	0.49	7.86 ± 1.19	8.16 ± 0.95	0.24
Pmax (W/kg)	15.5 ± 1.8	17.0 ± 2.4	0.50	17.0 ± 3.3	17.4 ± 2.5	0.14
S_{Fv}	-0.94 ± 0.08	-1.00 ± 0.17	-0.39	-0.94 ± 0.13	-0.99 ± 0.11	-0.27

Note. WR = wearable resistance; ES = effect size; * = indicates a statistically significant (p-value ≤ 0.05) difference for the effect of training group in the linear regression analysis; V0 = theoretical maximum velocity; F0 = theoretical maximum horizontal force; Pmax = maximum horizontal power output; S_{Fv} = slope of the force-velocity profile

Table 28. Kinematic variables (mean ± SD) from the start, acceleration and maximum velocity phases before and after a six-week training intervention.

	Control Group			WR Intervention Group		
	Pre	**Post**	**ES**	**Pre**	**Post**	**ES**
START PHASE:						
Flight Time (s)	0.051 ± 0.014	0.048 ± 0.017	-0.16	0.052 ± 0.012	0.054 ± 0.010	0.16
Contact Time (s)	0.209 ± 0.013	0.206 ± 0.009	-0.33	0.202 ± 0.019	0.203 ± 0.023	0.03
Step Frequency (Hz)	3.88 ± 0.21	3.97 ± 0.27	0.34	3.99 ± 0.25	3.94 ± 0.33	-0.20
Step Length (m)	1.18 ± 0.09	1.19 ± 0.12	0.05	1.21 ± 0.10	1.22 ± 0.10	0.16
Vertical Stiffness (kN/m/kg)	0.141 ± 0.019	0.143 ± 0.013	0.18	0.155 ± 0.031	0.155 ± 0.040	0.05
ACCELERATION PHASE:						
Flight Time (s)	0.073 ± 0.013	0.073 ± 0.015	0.02	0.075 ± 0.012	0.082 ± 0.011	0.45 *
Contact Time (s)	0.165 ± 0.007	0.159 ± 0.008	-0.73	0.158 ± 0.012	0.153 ± 0.012	-0.64
Step Frequency (Hz)	4.22 ± 0.17	4.33 ± 0.24	0.43	4.31 ± 0.18	4.29 ± 0.26	-0.10 *
Step Length (m)	1.51 ± 0.11	1.52 ± 0.12	0.05	1.56 ± 0.12	1.58 ± 0.12	0.15
Vertical Stiffness (kN/n/kg)	0.239 ± 0.026	0.257 ± 0.029	0.60	0.265 ± 0.046	0.287 ± 0.050	0.74
MAXIMUM VELOCITY PHASE:						
Flight Time (s)	0.118 ± 0.015	0.116 ± 0.014	-0.11	0.126 ± 0.017	0.126 ± 0.015	0.01
Contact Time (s)	0.119 ± 0.009	0.117 ± 0.012	-0.20	0.113 ± 0.012	0.110 ± 0.009	-0.22
Step Frequency (Hz)	4.24 ± 0.24	4.30 ± 0.23	0.29	4.22 ± 0.36	4.26 ± 0.29	0.16
Step Length (m)	1.89 ± 0.12	1.89 ± 0.13	0.02	1.98 ± 0.18	1.96 ± 0.17	-0.10
Vertical Stiffness (kN/m/kg)	0.508 ± 0.089	0.534 ± 0.110	0.23	0.588 ± 0.155	0.639 ± 0.127	0.46

Note. WR = wearable resistance; ES = effect size; * = indicates a statistically significant (p-value ≤ 0.05) difference for the effect of training group in the linear regression analysis

Table 29. Inertial load cycle test results and isokinetic strength (peak torque) test results (mean ± SD) from before and after a six-week training intervention.

	Control Group			WR Intervention Group		
	Pre	**Post**	**ES**	**Pre**	**Post**	**ES**
ISOKINETIC STRENGTH TEST:						
Hip Ext. Torque 60 °/s (N/kg)	3.33 ± 0.50	3.45 ± 0.46	0.25	3.31 ± 0.40	3.45 ± 0.50	0.30
Hip Flex. Torque 60 °/s (N/kg)	1.66 ± 0.29	1.76 ± 0.28	0.36	1.83 ± 0.28	1.88 ± 0.23	0.17
Hip Ext. Torque 180 °/s (N/kg)	2.47 ± 0.36	2.62 ± 0.31	0.47	2.44 ± 0.46	2.71 ± 0.36	0.87
Hip Flex. Torque 180 °/s (N/kg)	1.34 ± 0.19	1.43 ± 0.17	0.52	1.49 ± 0.22	1.57 ± 0.17	0.43
INERTIAL LOAD CYCLE TEST:						
PP_{IL} (W/kg)	11.9 ± 1.4	12.5 ± 1.6	0.40	12.7 ± 1.8	12.9 ± 1.5	0.10
Optimal Cadence (rpm)	128 ± 10	127 ± 9	-0.17	128 ± 9	128 ± 9	0.08

Note. WR = wearable resistance; ES = effect size; Ext = extension; Flex. = flexion; PP_{IL} = peak power output during inertial load cycle ergometer test; * = indicates a statistically significant (p-value ≤ 0.05) difference for the effect of training group in the linear regression analysis

Discussion and Implications

This was the first lower body WR training study to combine sprint performance results with kinematic and kinetic results during both the acceleration and maximum velocity sprint phases. The main findings of the study were: 1) there was a small improvement in sprint acceleration performance after the six-week training intervention, but there was no additional benefit due to training with WR; 2) changes in acceleration phase FT and SF were different when the speed training was completed with or without WR; and, 3) there was a small to moderate increase in hip flexion and extension torque after the training intervention, but no significant difference between the WR and control groups. Inconsistent adherence to the training program may have impacted on the outcomes and should be considered when assessing the findings of the study.

The small improvements in sprint performance after six weeks of training were in the magnitude of 1-3% at the most, and there was no evidence of improved maximum velocity performance in the WR intervention group. The hypothesis that sprint performance would improve more in the WR training group compared to the control group must be rejected as there was no statistically significant training group effect of the intervention on sprint performance. In fact, more consistent small effects were observed in the control group (including sprint split times, F0 and Pmax), while the WR group demonstrated a small improvement in 10 m split times only. Other sprint intervention studies of a similar length reported changes in 10 m split times of up to 5% (Kawamori, Newton, et al., 2013; Lockie et al., 2012), however Kawamori, Newton, et al. (2013) used three training sessions per week instead of two. Gabbett, Johns, and Riemann (2008) reported little or no change in speed performance in young rugby league players after 10 weeks of training. The training intervention used in this study was insufficient to achieve moderate changes in sprint performance within the sample of young rugby players. Other than rugby trainings and games, the participants were not involved in any other structured training programs. Participants may have benefited from additional training each week that aimed to improve speed performance, or a training program that focused either on the acceleration phase or the maximum velocity phase, rather than attempting to cover both aspects within two weekly 60 minute sessions.

It was assumed that the intervention group performed more rotational mechanical work at the hips and knees due to the greater mechanical load with lower body WR. If this assumption was accurate, the WR group athletes may have benefited from additional within session recovery or shortened total sessions compared to the control group. Insufficient recovery between loaded, longer sprint repetitions could have negatively impacted on the quality of the speed sessions. Mechanical work was however not measured, and it is possible that changes such as reduced angular displacement with WR meant that there was no additional rotational overload in the intervention group compared to the control group. Future research needs to ensure rotational workload is measured in some manner to understand the adaptations or lack of, associated with WR limb loading.

Changes in sprint kinematics were largely consistent between the two training groups in this study, however the changes in acceleration phase FT and SF were significantly different between the groups. It seems given the concurrent decrease in ground CT during the acceleration phase, the speed improvements were achieved through a strategy of increasing FT (9%) within the WR group, but through a strategy of increasing SF (2%) in the control group. In the only other lower body WR training study, acceleration phase kinematics were not measured, but maximum velocity phase FT was significantly lower (-6%) and SL was significantly longer (5%) after six weeks of training (Pajic, 2011). In contrast in this study there was no evidence of the negative interaction known to exist between FT and SL (Mackala, 2007; Nagahara et al., 2014). Instead there was a small decrease in CT (-2%), with unchanged FT and SL. Differences between the studies included that the participants in the study of Pajic (2011) were untrained and the loading protocol used was more intense, with 5% BM loading used throughout the intervention. Heavy lower body WR (5% BM) is known to significantly overload maximum velocity phase SL acutely (*unpublished findings,* Chapter 9), while lighter loading (3% BM) does not (Macadam, Simperingham, & Cronin, 2017). It seems the heavier lower body stimulus repeated over a period of six weeks was enough to chronically increase SL (Pajic, 2011), but 5% BM loading included in the final week of training in the present study was not a sufficient stimulus to positively impact on SL. It should also be noted that maximum velocity was not substantially changed in either study.

It was hypothesised that lower body WR training may be effective at overloading the hip flexors and causing a positive training effect on hip flexor moment, which is known to be associated with sprint performance (Ema et al., 2018). While there was a small to moderate post-training improvement in hip flexor and extensor torque in the WR group (5-11% at 180°/s), a similar pattern of improvement (6-7%) was also evident within the control group. If there are added hip strength benefits to speed training with lower body WR, the time course of changes exceeds six weeks of bi-weekly training with 1-5% BM loading.

It has been proposed that muscle fibre type may influence the effectiveness of acute improvements in sprint performance after a ballistic exercise pre-conditioning stimulus (Maloney et al., 2014; Tillin & Bishop, 2009), however there is little supporting objective evidence in the literature (Smith et al., 2014). Researchers have previously reported that optimal cadence (i.e. the pedaling rate at PP_{IL}) during a cycle ergometer sprint test was strongly correlated ($r = 0.88$) with the fast twitch muscle fibre cross sectional area of vastus lateralis (Hautier et al., 1996), which in separate studies was also correlated with sprint-running performance (Mero, Luhtanen, Viitasalo, & Komi, 1981). The inertial load cycle sprint test was therefore included as a proxy measurement for changes in muscle fibre composition after the WR training intervention in this study and also as a potential method of stratifying the group when analysing different individual responses to the sprint training program. There was no evidence of a change in optimal cadence after the six-week training program. When stratifying the group into those with a relatively high optimal cadence (> 130 revolutions per minute) and that had completed at least 80% (10 out of 12) of the prescribed training sessions, there were only four participants in the group (three from the WR group and one from the control group). Unfortunately comparing group means with such a small sample was not relevant, but future research should focus on exploring this area further.

Only 17% of all participants (four out of 23) completed all 12 prescribed speed training sessions, and nine participants missed four or more sessions. Therefore, training adherence may well have impacted on the study outcomes. Additional limitations of the study included the difficulty in equating and managing mechanical work completed between the control and intervention groups, the potential impact of fatigue from pre-season rugby games and the timing of post-testing. As mentioned above, longer intra-session rest periods between loaded sprints compared to unloaded sprints may have improved the quality of the speed sessions, particularly for longer sprint distances and heavier WR loads. Ensuring the training program is optimised for both control and WR groups is important to enable a relevant comparison between the groups. All participants took part in pre-season rugby games between the end of the speed training intervention and the post-testing session. Rugby games can induce substantial muscle damage (Tavares, Smith, & Driller, 2017), so the timing of the post-testing less than 48 hours after a pre-season game was not ideal. It is also possible that effects of the training intervention may take longer than two weeks to impact on performance, so additional follow-up testing after a month or more could be incorporated into future research. The participants in the current study were young rugby players, with a low training age and minimal previous experience with structured speed training. Future research should include assessments and training of change of direction/agility and compare the effects of training with lower body WR with different groups of athletes without the confounding influence/fatigue of competitive games. Assessment of factors that may be associated with responders and non-responders to the WR training interventions could also enhance the understanding of the area.

Conclusions

Six weeks of speed training led to small improvements in acceleration phase sprint performance and hip strength particularly at fast movement velocity, but there was no additional benefit to training with lower body WR and no evidence of improved maximum velocity performance in the WR group. Changes in acceleration phase FT and SF were significantly different between the training groups. Training with WR resulted in increased acceleration phase FT, instead of increased SF in the control group. Inadequate adherence and therefore inadequate training frequency may have affected potential adaptation for both groups. Monitoring rotational workload in future training studies will be important to quantify the specific impact of WR training. Future research should assess the effects of lower body WR training interventions within diverse athletic groups and include assessments of the impact on change of direction training and maximum velocity over longer distances.

CHAPTER 12

SUMMARY, PRACTICAL APPLICATIONS AND FUTURE RESEARCH DIRECTIONS

The overarching question of this thesis was: “Can WR training enhance sprint-running performance?” Four underpinning research objectives were addressed in four separate inter-related sections of the thesis. The key conclusions from each section are summarised below. Ultimately the aim of the research was to develop WR speed training guidelines, which are detailed in the Practical Applications section. Finally, the limitations associated with this thesis are discussed and suggestions for future research are detailed.

Key Findings – Section 1

Quantifying sprint performance with valid and reliable methods is crucial in order to assess the effectiveness of sprint training interventions. Providing insight into some of the kinematic and kinetic determinants of sprinting performance, including quantifying horizontal GRF during the acceleration phase, is important for sprint acceleration profiling to have true diagnostic value. Section 1 (Chapters 2-4) focused on the utility and accuracy of the advanced testing technologies of radar and laser devices, and NMT and TT. Specifically, the reliability of measuring horizontal force, velocity and power during short sprint-running accelerations was studied and the key findings were:

Radar and Laser Devices

1. The majority of radar-derived kinematic and kinetic descriptors of short sprint performance had acceptable intra-day and inter-day reliability (ICC $\geq$ 0.75 and CV $\leq$ 10%), but split times over the initial 10 m and some variables that included a horizontal force component had only moderate relative reliability (ICC = 0.49-0.74). The increasingly upright posture over the first few steps of an acceleration was proposed as one likely explanation, but the contribution of error due to post-processing techniques was not ruled out.
2. Comparing the average of two sprint trials between days resulted in acceptable reliability for all radar-derived variables except the relative slope of the force-velocity relationship (S_{Fvrel}; ICC = 0.74). Therefore, practitioners should average sprint test results over at least

two trials to reduce measurement variability, particularly for outcome variables with a horizontal force component and for sprint distances of less than 10 m from the start.

Non-Motorised Treadmill (NMT) and Torque Treadmill Devices

3. Important testing protocols that can help to improve NMT and torque treadmill testing reliability include: suitable familiarisation, a treadmill sampling rate of ≥ 200 Hz, a "blocked" starting position, averaging results over multiple sprints and analysing discrete steps rather than arbitrary time windows.
4. Even after an extended treadmill warm-up, one familiarisation session was required to achieve moderate to acceptable reliability of NMT-derived variables and ensure no further learning effects.
5. Intra-day reliability was moderate to acceptable (ICC ≥ 0.63, CV ≤ 6.4%) for all kinematic and kinetic variables (except acceleration phase FT) during the acceleration (steps 3-12) and maximum velocity (steps 13-22) phases, but unacceptable during the start phase (steps 1-2).
6. Consistent with radar device findings, rather than comparing the first or best sprint trials over time, practitioners should average NMT/torque treadmill sprint test results over at least two trials to optimise the reliability of data and therefore enhance the accuracy of the diagnostic and reporting process.

Key Findings – Section 2

Two interrelated speed training techniques were reviewed in Section 2: WR training, focusing on lower body WR (Chapter 5); and the acute effects of loaded and unloaded ballistic exercise on subsequent sprint-running performance (Chapter 6). These literature reviews included a summary and evaluation of relevant research findings and importantly identified knowledge gaps in the literature that could be addressed in the subsequent sections of the thesis and future research. The key findings were:

Lower Body WR Training

1. Upper body WR of > 10% BM had a significant acute impact on the biomechanics of sprinting and running in previous research, but substantially lighter (≤ 5% BM) WR attached to the lower body resulted in significantly increased ground CT and decreased SF in most acute assessments of the acceleration phase and the maximum velocity phase of sprinting.
2. Longitudinal analysis of lower body WR and sprinting was limited to one six-week training study of an untrained sample. Maximum velocity was unchanged (although SF was reduced -6% and SL was increased 5%), and acceleration performance was not assessed.

Acute Performance Enhancement (APE) Effects of Ballistic Exercise (BE)

3. Significant APE of sprint performance can occur 15 seconds to 16 minutes after loaded and unloaded BE. The following APE optimal rest period guidelines were proposed:
    - Approximately 1 minute after unloaded jumps with < 10 jump contacts.
    - 4-16 minutes after loaded jumps and unloaded jumps with ≥ 10 jump contacts.
    - 8-12 minutes after heavy (50-75% BM) resisted sprints.
    - Approximately 7 minutes after heavy power cleans.
    - A longer rest period may tend to be optimal when the APE target is the maximum velocity phase rather than the acceleration phase.

Key Findings – Section 3

Section 3 involved implementing the reliable and beneficial sprint acceleration profiling methods identified in Section 1 during four cross-sectional studies addressing several of the gaps in the WR literature that were earlier summarised in Table 11 (Section 2). The key findings from Section 3 of this thesis were added to Table 11 to illustrate the expanded knowledge of the area (Table 30). The key findings from Section 3 were:

Upper Body vs Lower Body WR During Sprint-Running

1. Vertical GRF was significantly higher (in absolute and relative terms) by 2-6% with lower body WR (5% BM) compared to the same magnitude of upper body WR during both the acceleration phase and the maximum velocity phase of treadmill sprinting. It could be speculated that the reduced F_v with upper body loading was due to a reduction in the maximum displacement of the centre of mass while sprinting with upper body loading due to the significant decrease in FT. Conversely, FT and also functional F_v during sprinting with lower body WR were unchanged compared to unloaded sprinting.
2. Sprinting speed was not significantly changed over the initial 10 m of a treadmill sprint with lower body WR (5% BM), however split times > 10 m and maximum velocity were significantly impaired (-2 to -5%).
3. Ground CT was significantly longer (4-5%) and SF was significantly lower (-4%) during both the acceleration phase and the maximum velocity phase of treadmill sprinting with lower body WR (5% BM).
4. Most participants perceived improved unloaded sprint performance 4-6 minutes after completing four sprints with WR, however the only statistically significant change measured was increased (1%) vertical GRF during the maximum velocity phase compared to baseline unloaded sprinting.

Acceleration Phase Sprint Biomechanics with Lower Body WR

5. Consistent with treadmill sprinting, over-ground sprinting with 3-5% BM lower body WR resulted in significantly increased CT (5-6%) and decreased SF (-2 to -3%).
6. Moderate lower body WR loading (3% BM) resulted in increased functional F0 and combined with likely increased muscular activity resulted in unchanged 20 m sprint time compared to unloaded sprinting.
7. Heavy lower body WR loading (5% BM) resulted in a significant decrease (-4%) in effective F_v and a significant increase (4%) in 20 m sprint time.

Maximum Velocity Phase Sprint Biomechanics with Lower Body WR

8. The percentage decrement in maximum sprint velocity was approximately equivalent to the magnitude of the lower body loading relative to participant BM (i.e. 3-5%).
9. Lower body WR (3-5% BM) significantly overloaded ground CT (4-5%), SL (-2%; 5% BM WR only), SF (-3%), vertical stiffness (-8 to -9%) and treadmill-derived horizontal effective sprint kinetics (-5 to -7%; 5% BM WR only).

APE Effects of Ballistic Exercise with WR

10. Lower body WR (3-5% BM) worn during either a dynamic speed warm-up or a series of 40 m sprints appears to be effective at acutely enhancing subsequent unloaded sprint acceleration performance after a rest period of 5-15 minutes. Directly loading the sprint cycle (rather than loaded drop jumps) was more effective at eliciting an APE effect.

Table 30. Acute changes in sprinting speed, kinematics and kinetics during the acceleration and maximum velocity sprint phases with light, moderate and heavy lower body WR. Findings contributed from this thesis are shaded in grey.

			Light WR (≤ 2% BM)			**Moderate WR (3-4% BM)**			**Heavy WR (≥ 5% BM)**		
			Whole Leg	***Thigh***	***Shank***	***Whole Leg***	***Thigh***	***Shank***	***Whole Leg***	***Thigh***	***Shank***
Acceleration Phase (0-20 m)	**Speed**	0-10 m	↔	↔	↔	↔			↔		
		0.5-15 m			↓ 3.6%			↓ 4.6%			↓ 7.8%
		10-20 m	↓ 4.2%			**↓ 2.2-2.9%**			**↓ 5.2%**		
		20 m				↔			**↓ 2.0-2.5%**		
		V0				**↓ 5.4-6.5%**					
	Kinematics	CT		↔	↔	**↑ 3.4-6.0%**			**↑ 4.3-5.7%**		
		FT		↔	↔	↔			↔		
		SL		↔	↔	↔			↔		
		SF		↔	↓ 2.1%	**↓ 1.7-3.0%**			**↓ 2.6-3.7%**		
	Kinetics	F_v				↔			**pk/avg↓ 4%**		
		F_h				**pk..↔** **avg. ↓ 4.3%**			**pk..↔** **avg. ↓ 6.4%**		
		F0				↔			↔		
		S_{Fv}				**↓ 9.9-12.0%**			↔		
		Pmax				**pk ↔** **avg ↓ 5.0%**			**pk ↔** **avg ↓ 7.6%**		

			Light WR (≤ 2% BM)			Moderate WR (3-4% BM)			Heavy WR (≥ 5% BM)		
			Whole Leg	***Thigh***	***Shank***	***Whole Leg***	***Thigh***	***Shank***	***Whole Leg***	***Thigh***	***Shank***
Maximum Velocity Phase (≥ 20 m)	**Speed**	15-30 m			↓ 4.2%			↓ 8.5%			↓ 12.8%
		20—30 m	↔			**↓ 3.0%**			**↓ 5.7%**		
		30—40 m	↓ 7.4%								
		40 m	↔								
		50 m		↔	↔						
		vmax		↓ 1.8%	↓ 1.4-2.3%	**↓ 2.9%**			**↓ 4.9-5.3%**		
		V0				**↓ 3.7%**			**↓ 5.0%**		
	Kinematics	CT	↔ (↑8.9%)	↑ 2.5-2.9%	↑ 1.2-2.1%	**↑ 4.3%**			**↑ 4.7-5.1%**		
		FT	↔	↔	↑ 2.8-3.3%	↔			↔		
		SL		↔	↔	↔			**↓ 2.0%**		
		SF	↔	↓ 1.4-3.7%	↓ 2.3%	**↓ 2.6%**			**↓ 3.4-3.5%**		
		kvert				**↓ 9.2%**			**↓ 9.3%**		
	Kinetics	F_v				↔			↔		
		F_h				↔			**pk ↔** **avg ↓ 4.7%**		
		Pmax				↔			**pk ↔** **avg ↓ 7.3%**		

Note. Compared to unloaded sprinting: ↓ = a statistically significant decrement (sprinting speed) or decrease; ↑ = a statistically significant increase; WR = wearable resistance; BM = body mass; V0 = theoretical maximum velocity; CT = contact time; FT = flight time; SL = step length; SF = step frequency; F_v = vertical ground reaction force; F_h = horizontal ground reaction force; F0 = theoretical maximum horizontal force; Pmax = maximum horizontal power output; vmax = maximum velocity; kvert = vertical stiffness; pk = peak; avg = average

Key Findings – Section 4

After improving the understanding of the acute changes in sprint performance and sprint biomechanics during sprinting with lower body WR (Section 3), the important next step was to quantify the longitudinal changes that occur after a period of speed training with lower body WR. Section 4 involved expanding on the one previous lower body WR training study in the area and implementing a six-week speed training intervention with a group of team sport athletes. Participants were randomly allocated into the intervention (WR) group or control (no WR) group. The WR group had external weight of up to 5% body mass attached to the legs during large parts of the training sessions, but intra-session contrast loading protocols were also used to potentially benefit from APE of sprint performance following a loaded warm-up or loaded sprints. The main findings of the training study were:

1. Changes in acceleration phase FT and SF were different when speed training was completed with or without lower body WR. Start phase and maximum velocity phase kinematic changes were consistent between the groups.
2. The small improvements in sprint performance (1-3%) and hip strength (3-11%) were consistent between the WR and control groups, so it was concluded that there was no additional benefit to training with lower body WR.
3. Inconsistent adherence to the training program may have negatively impacted on training outcomes.
4. Further consideration may be needed to account for the additive fatigue associated with the WR loading during activity matched training.

Practical Applications

The key aim of this research was to develop WR speed training guidelines for team sport athletes and coaches, based on an improved understanding of the acute and chronic biomechanical and performance changes that occur with speed training with lower body WR. Practical applications and training recommendations regarding sprint profiling and sprint training with lower body WR are proposed based on the current level of understanding from the key findings of this thesis as well as related research. The knowledge associated with both topics continues to expand and it is anticipated that the practical applications will therefore shift over time.

Training philosophy priorities will determine if athletes and coaches focus more on developing general capacities or focus more on training specificity. Traditional (general) overload involves focusing on Newtonian and physiological overload of capacities such as strength and aerobic capacity at the expense of time spent on training specificity. The addition of sport skill practice in parallel with this traditional approach to physical training is theorised to be sufficient to achieve training transfer to improved sport performance. Practitioners and athletes with more of a bias towards the other end of the specificity continuum will focus significant time on skill development over capacity development, and training movements with a high degree of similarity of the target sport skill movement. WR appears to be a training technique with diverse applications for individuals prioritising training specificity and those with a mixed-methods approach where general and specific training approaches are blended depending on the training goals.

While there is currently an absence of evidence of any chronic benefit of lower body WR training for improved sprint performance, it is too early to conclude that this constitutes evidence of an absence of any training effect. Further learnings will occur from the practical application of the thesis findings, combined with the application of basic principles of physics and in parallel with ongoing acute and chronic research studies in the area.

Sprint Profiling

- Radar/laser and NMT/torque treadmill devices are practical and reliable technologies that can be used to efficiently provide information about both sprinting performance and some of the key kinematic and kinetic determinants of that performance.
- Practitioners should follow the testing protocols outlined in this thesis to optimise reliability of the testing and generate practically meaningful results. Averaging sprint test results over two trials, particularly for radar-derived values with a horizontal force

component or split times ≤ 5 m, is an important modification to conventional practices of monitoring the best sprint trial.

WR and Sprinting

- The precise effects of various load orientations (e.g. anterior vs posterior, medial vs lateral load placement) are not yet well understood. However, by applying principles of physics (i.e. adjusting the position of the load in relation to the axis of rotation) greater rotational loading to the limbs can be achieved with relatively distal loading compared to proximal loading. Proximal to distal loading adjustments can therefore be used as a means of progressive overload of WR training.
- Vest loading (5% BM) provides a vertical loading stimulus, but results in significantly lower relative F_v during the acceleration phase and maximum velocity phase compared to unloaded sprinting. Lower body loading provides both a vertical and rotational overload during sprinting.

WR and Acceleration Phase Sprint Training

- Lower body WR of up to 5% BM provides specific overload to acceleration phase CT and FT while sprint mechanics were altered by no more than 6%.
- WR should be spread evenly across the legs and progressed over time by increasing the magnitude of the load and/or shifting from proximal loading configurations towards more distal loading configurations.
- Familiarisation of sprinting with lower body WR should start with light lower body WR (1-2% BM).
- Progressing to moderate lower body WR (3% BM) will result in an acute increase in maximal functional horizontal force production during acceleration, while acceleration sprint times and effective F_v will not be significantly affected. Mean acceleration phase F_h and Pmax will, however, be overloaded at this level of WR loading.

- Finally, by progressing to heavy lower body WR (5% BM), sprint times ≤ 10 m will still be maintained, but 10-20 m sprinting speed, horizontal and vertical GRF and vertical stiffness will all acutely be significantly lower.
- Speculation includes that lower body WR worn during sprinting may kinaesthetically reinforce ideal sprint acceleration mechanics by providing strong negative feedback for letting the lower shank swing through and may also possibly encourage a more horizontal GRF application, which is important for acceleration performance. It should, however, be noted that there is currently no longitudinal research establishing sprint training with lower body WR to be superior to conventional sprint training.

WR and Maximum Velocity Phase Sprint Training

- Lower body WR is a specific speed training tool that can overload maximum velocity phase CT, SF and at heavy loads also overload SL and horizontal force production.
- Compared to the acceleration phase, lower body WR has a greater impact on the maximum velocity phase most likely due to the greater angular momentum and kinetic energy of the faster, more circular limb motion during this phase. Greater muscular work requirements are therefore expected of the involved musculature compared to the acceleration phase.
- Lower body WR as low as 3% BM is sufficient to result in significantly reduced maximum sprint velocity. The percentage decrement in maximum velocity will approximate the relative magnitude of WR loading (i.e. 3-5%). Practitioners can simply periodise the planned maximum velocity phase overload based on relative WR loading.
- Maximum velocity is the product of SL and SF and a negative interaction is known to exist between SL and SF, so improving speed by increasing both of these variables is difficult. Moderate lower body WR (3% BM) results in overloading of SF without altering SL, so this magnitude of loading appears to be a suitable training method to improve these key determinants of speed.
- Attempting to maintain baseline CT during the maximal velocity phase while sprinting with light to moderate WR (1-3% BM) may be an effective specific training technique to

chronically increase vertical stiffness and therefore potentially maximum velocity. Real time CT feedback from tools such as Optojump could help to facilitate this training technique.

- It should be noted however that neither of the lower body WR training studies to date have established a clear maximum velocity phase benefit of training with WR compared to traditional unloaded speed training.

WR and APE of Sprinting

- Until further research is completed in the area, the following optimal rest period guidelines can be used for the APE of sprint performance following loaded BE:
    - 4-12 minutes after loaded jumps.
    - 5-15 minutes after a loaded warm-up or loaded sprints.
    - A longer rest period should be selected from within the optimal rest period guidelines when the APE target is the maximum velocity phase rather than the acceleration phase.
- Using lower body WR (3-5% BM) to load a dynamic speed warm-up or sprint accelerations appears to be more effective than loaded vertical jumps for eliciting an APE response in subsequent unloaded sprint performance. A loaded warm-up followed by a block of unloaded sprints is also likely to be practically more efficient than incorporating multiple long breaks within a speed session in order to achieve an optimal rest period length for APE.

Limitations

Limitations of this research included:

- The participants included in Chapters 3, 4, 8, 9 and 11 were young (average age: 18 years), relatively heavy (average BM: 91-97 kg), male, rugby union athletes with little structured speed and strength training experience. The participants in Chapter 7 were recreationally active team sport players (average age: 29 years; average BM: 82 kg), while a former international rugby representative volunteered for the study in Chapter 10 (age: 29 years; BM: 87 kg). Each of the participants were team sport athletes, however care should be taken in extrapolating the findings to substantially different populations. Specifically, the acute and chronic effect of WR training may well differ within individuals with better sprint mechanics, a higher top speed or other differences in physical characteristics.

- All participants included in the thesis had little or no experience training with WR. Different outcomes may be expected with individuals that are more accustomed to training with WR.
- The sample sizes in the cross-sectional group studies were 8-15 participants, while the training study finished with 10 and 13 participants in each group. Larger sample sizes would have improved the ability to detect a difference (if one exists), reducing the risk of type II error.
- Inconsistent adherence in the training study was potentially influential to the final conclusions of the study.
- Due to the absence of sufficient in-ground force plates in series, radar, Optojump, high-speed video and NMT technologies were used to provide estimations of sprint kinematics and kinetics. Some differences with gold standard testing equipment may be anticipated, so replicating the studies on force plates and with three-dimensional motion capture would be beneficial.
- A limited number of kinematic and kinetic variables were monitored. Analysis of joint angles, joint torques and qualitative aspects of sprint technique could enhance the understanding of the research area.

Future Research Directions

Future WR research should build upon the limitations of this thesis by assessing the acute impact of WR during over-ground sprinting on in-ground force plates synchronised with three-dimensional video motion capture to also enable assessment of joint angles and torques. A greater range of loading magnitudes (< 3% BM and > 5% BM) and placements should be analysed and compared. Combined upper and lower body loading configurations were analysed during constant pace running, but analysing these novel loading configurations during sprinting would be beneficial.

Sprint training with lower body WR is a developing area, so as further training studies are completed substantial gains in specific knowledge can be made. Future training studies should take account of some of the limitations detailed in Chapter 11. Consideration should be given to: a training intervention period longer than 6 weeks, and potentially including more time training with heavier loads; speed training and loading configurations targeting either the acceleration phase or the maximum velocity phase, rather than both; repeated follow-up testing up to several weeks after the training intervention; testing diverse athletic groups; using crossover training studies and comparing factors that may be associated with responders and non-responders to WR training interventions; and accounting for the additive load and fatigue associated with WR loading during activity matched training.

Future research in the area of APE of sprinting should re-investigate some of the pre-conditioning stimuli trialled in Chapter 10, including loaded warm-ups and other ballistic exercises with added intensity from WR. Single subject research design can be considered relatively weak evidence, so future research should investigate this area with an expanded sample of participants. The loaded ballistic exercise protocols are easy to practically implement and potentially useful in both training and competition scenarios.

The capability to flexibly load the lower body now makes it much easier to load sport-specific acceleration, maximum velocity and change of direction training drills. Until now the specific overload of change of direction and agility training for team sport athletes has been very difficult, so future research should investigate the impact of this novel sport-specific application of WR training.

Future research should also focus on understanding the direct impact of various WR loading configurations by using three-dimensional motion analysis and inertial sensors to quantify the changes in kinetic energy and muscular output. Ultimately, barriers to the application of WR training will be reduced if practitioners and athletes can easily and quickly understand the impact on muscular output of subtle changes in WR load magnitudes and placements (e.g. proximal vs distal positioning).

One of the benefits of sprint profiling with radar or laser devices is that relatively force-dominant and relatively velocity-dominant individuals can be identified from the slope of their force-velocity profile and sprint training can be individualised based on the results. Future research should analyse whether WR training is more effective for force-dominant or velocity-dominant individuals. Ultimately individualised usage of WR to achieve specific speed goals is the opportunity facilitated by recent advancements in WR technology. Ongoing WR research will be crucial to arm practitioners with relevant knowledge regarding the specific loading types that affect the mechanical determinants of sprint performance and to enable individuals from team sports and other sports to use targeted WR loading strategies to individualise sprint training and optimise their sprint potential.

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APPENDICES

Appendix A. Ethical Approval for Chapters 3-4

AUTEC
SECRETARIAT

5 September 2014

John Cronin
Faculty of Health and Environmental Sciences

Dear John

Re Ethics Application: **14/238 The reliability of three sprint testing modalities for team sport athletes.**

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

Your ethics application has been approved for three years until 5 September 2017.

As part of the ethics approval process, you are required to submit the following to AUTEC:

- A brief annual progress report using form EA2, which is available online through http://www.aut.ac.nz/researchethics. When necessary this form may also be used to request an extension of the approval at least one month prior to its expiry on 5 September 2017;
- A brief report on the status of the project using form EA3, which is available online through http://www.aut.ac.nz/researchethics. This report is to be submitted either when the approval expires on 5 September 2017 or on completion of the project.

It is a condition of approval that AUTEC is notified of any adverse events or if the research does not commence. AUTEC approval needs to be sought for any alteration to the research, including any alteration of or addition to any documents that are provided to participants. You are responsible for ensuring that research undertaken under this approval occurs within the parameters outlined in the approved application.

AUTEC grants ethical approval only. If you require management approval from an institution or organisation for your research, then you will need to obtain this. If your research is undertaken within a jurisdiction outside New Zealand, you will need to make the arrangements necessary to meet the legal and ethical requirements that apply there.

To enable us to provide you with efficient service, please use the application number and study title in all correspondence with us. If you have any enquiries about this application, or anything else, please do contact us at ethics@aut.ac.nz.

All the very best with your research,

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

Cc: Kim Simperingham ksimperingham@gmail.com

Appendix B. Participant Information Sheet Chapters 3-4

Participant Information Sheet

AUT UNIVERSITY
TE WĀNANGA ARONUI O TAMAKI MAKAU RAU

Date Information Sheet Produced:

14 July 2014

Project Title

The reliability of three sprint testing modalities for team sport athletes

An Invitation

My name is Kim Simperingham 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. We are currently conducting a study into sprint testing and training options for team sport athletes and would like to invite you to participate in the research. Your participation would be greatly valued, but is entirely voluntary and you may withdraw at any time prior to the completion of the data collection. The results from this project will be used in the first section of my doctoral thesis.

What is the purpose of this research?

The purpose of this research is to establish the reliability and/or validity of three advanced sprint testing options for measuring force, speed and power. Short sprint-running accelerations will be measured with radar and non-motorised treadmill (NMT) technology, while short sprint-cycling accelerations will be measured with a custom-built stationary cycle. The research findings will be reported in my doctoral thesis as well as conference presentation(s) and scientific journal article(s).

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

The participants for this project are required to be healthy, injury-free field-based team sport athletes aged 18-35 years old. An invitation was sent to your provincial union to distribute to potential participants and you have been identified as meeting the inclusion criteria for this project. If people do not meet all of the inclusion criteria (healthy, injury-free, field-based team sport athlete, aged 18-35 years), they will be excluded from the study.

What will happen in this research?

If you chose to participate in this project, you will be required to attend four 1.5 – 2 hour testing sessions at the AUT Millennium Campus strength and conditioning laboratories. The four testing sessions will each be one week apart and conducted on the same day of the week. The first testing session will involve familiarisation with all testing procedures and equipment (particularly the NMT and cycle tests). Testing sessions 2-4 will each be identical and will involve a 20 min standardised warm-up followed by three maximal-effort sprints on the three testing modalities:

(i) 3x 30 m over-ground sprint-run on an indoor running track
(ii) 3x 6 s sprint-run on a treadmill
(iii) 3x 4 s sprint-cycle on a stationary cycle

A brief standardised treadmill-specific and cycle-specific warm-up will be completed prior to testing on the treadmill and stationary cycle respectively. You will have a recovery period of at least three minutes of rest before each maximal effort sprint.

What are the discomforts and risks?

There should be no significant discomforts or risks associated with this testing beyond those experienced during normal sprint 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.

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 at least 90 minutes prior to the start of testing. A comprehensive warm-up and cool-down will be performed before and after each testing session. Full recovery of at least three minutes of rest will be ensured before each maximal effort sprint.

What are the benefits?

Establishing the reliability of the three test modalities will benefit coaches and sport scientists by determining the stability of the different test options. Athletes will also benefit from these findings, which may ultimately lead to a more athlete-specific method of determining the ideal training stimulus from the range of effective training techniques available. The research findings will also be used to assist me in obtaining a PhD qualification. 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 ongoing strength and conditioning program decisions.

What compensation is available for injury or negligence?

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

How will my privacy be protected?

- 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 future research and shared with SPRINZ approved researchers.
- 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.

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 four testing sessions each of 1.5 - 2 hours (i.e. total time of up to 8 hours).

What opportunity do I have to consider this invitation?

- Please take the necessary time (up to 2 weeks) you need 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?

A summary of your results from the testing and the averages of all participants will be provided to you via email. 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, 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, 921 9999 ext 6038.

Whom do I contact for further information about this research?

Researcher Contact Details:

Kim Simperingham
Sports Performance Research in New Zealand (SPRINZ) at AUT Millennium Institute, Auckland University of Technology, 17 Antares Place, Mairangi Bay, Auckland 0632.
ksimperingham@gmail.com
021 1060 330

Project Supervisor Contact Details:

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

Approved by the Auckland University of Technology Ethics Committee on 5th September 2014, AUTEC Reference number 14/238.

Appendix C. Consent Form Chapters 3-4

Consent Form	AUT UNIVERSITY TE WĀNANGA ARONUI O TAMAKI MAKAU RAU

Project title: ***The reliability of three sprint testing modalities for team sport athletes***

Project Supervisor: ***Professor John Cronin***

Researcher: ***Kim Simperingham***

- ○ I have read and understood the information provided about this research project in the Information Sheet dated 14 July 2014.
- ○ 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 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:

  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 5th September 2014, AUTEC Reference number 14/238.

Note: The Participant should retain a copy of this form.

Appendix D. Ethical Approval for Chapters 7-11

AUTEC
SECRETARIAT

14 April 2015

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

Your ethics application has been approved for three years until 14 April 2018.

As part of the ethics approval process, you are required to submit the following to AUTEC:

- A brief annual progress report using form EA2, which is available online through http://www.aut.ac.nz/researchethics. When necessary this form may also be used to request an extension of the approval at least one month prior to its expiry on 14 April 2018;
- A brief report on the status of the project using form EA3, which is available online through http://www.aut.ac.nz/researchethics. This report is to be submitted either when the approval expires on 14 April 2018 or on completion of the project.

It is a condition of approval that AUTEC is notified of any adverse events or if the research does not commence. AUTEC approval needs to be sought for any alteration to the research, including any alteration of or addition to any documents that are provided to participants. You are responsible for ensuring that research undertaken under this approval occurs within the parameters outlined in the approved application.

AUTEC grants ethical approval only. If you require management approval from an institution or organisation for your research, then you will need to obtain this.

To enable us to provide you with efficient service, please use the application number and study title in all correspondence with us. If you have any enquiries about this application, or anything else, please do contact us at ethics@aut.ac.nz.

All the very best with your research,

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

Cc: Kim Simperingham ksimperingham@gmail.com

Appendix E. Participant Information Sheet Chapters 7-11

Participant Information Sheet

Date Information Sheet Produced:

18 December 2014

Project Title

Light Variable Resistance Training^{TM} with Exogen^{TM} Exoskeletons

An Invitation

My name is Kim Simperingham 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^{TM} 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^{TM}, the producer of Exogen^{TM}, will provide Exogen^{TM} 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^{TM} 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^{TM} 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 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) and the chronic changes that occur after a period of several weeks of training with added weight attached to the body. We will use relevant tests from a range of options: running and sprinting performance will be measured with radar and treadmill technology; short sprint-cycling accelerations will be measured with a custom-built stationary cycle; strength and jump performance will be assessed on a portable force platform and with video analysis; and body composition will be measured using skinfold testing with callipers. The research findings will be reported in my doctoral thesis as well as conference presentation(s) and scientific journal article(s).

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

The participants for this project are required to be healthy, injury-free recreationally- or competitively-active males and females aged 18-40 years old. You meet these criteria 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 one testing session at AUT Millennium for approximately two hours. If you choose to participate in the training study, the same testing session will be repeated after approximately 2-8 weeks of training with added weight attached to the Exogen suit.

You will complete a standardised warm-up prior to all testing and you will have a recovery period of at least three minutes before each maximal effort test. Following the standardised warm-up you will complete selected tests from the following list:

- Body composition assessment using skinfold callipers
- 30 m over-ground sprints and 15 m agility sprints
- 6 s sprints on a non-motorised treadmill
- Constant pace running on a motorised treadmill (including 3 dimensional [3D] motion analysis)
- 4 s cycle sprints on a stationary cycle ergometer
- Vertical, horizontal and lateral jumps (including 3D motion analysis)
- 3 s isometric mid-thigh pull strength test

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. If you are completing 3D motion analysis testing in the laboratory then you will be asked to complete the running and jumping 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, change of direction 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, rehabilitation and compensation for injury by accident may be available from the Accident Compensation Corporation, providing the incident details satisfy the requirements of the law and the Corporation's regulations.

How will my privacy be protected?

- We will take a number of 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 one testing session of approximately 2 hours for the acute study. For the training study the total time commitment will be two 2 hour testing sessions and 2-6 weekly training sessions during which you will be required to wear the Exogen exoskeleton with a specified amount of added weight attached.

What opportunity do I have to consider this invitation?

- Please take the necessary time (up to 2 weeks) you need 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, 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, 921 9999 ext 6038.

Whom do I contact for further information about this research?

Researcher Contact Details:

Kim Simperingham
Sports Performance Research Institute New Zealand (SPRINZ) at AUT Millennium, Auckland University of Technology, 17 Antares Place, Mairangi Bay, Auckland 0632.
ksimperingham@gmail.com
021 1060 330

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 0632.
john.cronin@aut.ac.nz
921 9999 ext 7523

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

Appendix F. Consent Form Chapters 7-11

Consent Form	AUT UNIVERSITY TE WĀNANGA ARONUI O TAMAKI MAKAU RAU

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

Project Supervisor: ***Professor John Cronin***

Researcher: ***Kim Simperingham***

○ I have read and understood the information provided about this research project in the Information Sheet dated 18 December 2014.

○ 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 (*acute study*).

Yes○ No○

○ I agree to take part in the *training study*.

Yes○ No○

○ 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 15 July 2015, AUTEC Reference number 15/07.

Note: The Participant should retain a copy of this form.

Appendix G. Publication: The effects of wearable resistance training on metabolic, kinematic and kinetic variables during walking, running, sprint running and jumping

This appendix comprises the abstract for the following publication in *Sports Medicine,* which was referenced in Chapter 5 and which KS was a research supervisor and co-author for during the period of PhD enrolment:

Macadam, P., Cronin, J. B., & Simperingham, K. D. (2017). The effects of wearable resistance training on metabolic, kinematic and kinetic variables during walking, running, sprint running and jumping: a systematic review. *Sports Medicine, 47*(5), 887-906.

Background: Wearable resistance training (WRT) provides a means of activity or movement specific overloading, supposedly resulting in better transference to dynamic sporting performance.

Objective: The purpose of this review was to quantify the acute and longitudinal metabolic, kinematic and/or kinetic changes that occur with WRT during walking, running, sprint-running or jumping movements.

Data Sources: PubMed, SPORTDiscus, Web of Science and MEDLINE (EBSCO) were searched using the Boolean phrases (limb OR vest OR trunk) AND (walk* OR run* OR sprint* OR jump* OR bound*) AND (metabolic OR kinetic OR kinematic) AND (load*).

Study Selection: A systematic approach was used to evaluate 1,185 articles. Articles with injury-free subjects of any age, sex or activity level were included.

Results: Thirty-two studies met the inclusion criteria and were retained for analysis. Acute trunk loading reduced velocity during treadmill sprint-running but only significantly when loads of 11% body mass (BM) or greater were used, while over the ground sprint-running times were significantly reduced with all loads (8-20% BM). Longitudinal trunk loading significantly increased jump performance with all loads (7-30% BM) but did not significantly improve sprint-running performance. Acute limb loading significantly increased maximum oxygen consumption and energy cost with all loads (0.3-8.5% BM) in walking and running, while significantly reducing velocity during sprint-running.

Limitations: The variation in load magnitude, load orientation, subjects, testing methods and

study duration no doubt impact the changes in the variables examined and hence make definitive conclusions problematic.

Conclusions: WRT provides a novel training method with potential to improve sporting performance, however, research in this area is still clearly in its infancy with future research required into the optimum load placement, orientation and magnitude required for adaptation.

Appendix H. Publication: Acute kinematic and kinetic adaptations to wearable resistance during vertical jumping

This appendix comprises the abstract for the following publication in *European Journal of Sport Science,* which was referenced in Chapter 5 and which KS was a research supervisor and co-author for during the period of PhD enrolment:

Macadam, P., Simperingham, K. D., Cronin, J. B., Couture, G., & Evison, C. (2017). Acute kinematic and kinetic adaptations to wearable resistance during vertical jumping. *Eur J Sport Sci, 17*(5), 555-562.

One variation of vertical jump (VJ) training is resisted or weighted jump training, where wearable resistance (WR) enables jumping to be overloaded in a movement specific manner. A two-way analysis of variance with Bonferroni post hoc contrasts was used to determine the acute changes in VJ performance with differing load magnitudes and load placements. Kinematic and kinetic data were quantified using a force plate and contact mat. Twenty sport active subjects (age: 27.8 ± 3.8 years; body mass (BM): 70.2 ± 12.2 kg; height: 1.74 ± 0.78 m) volunteered to participate in the study. Subjects performed the counter movement jump (CMJ), drop jump (DJ) and pogo jump (PJ) wearing no resistance, 3 or 6% BM affixed to the upper or lower body. The main finding in terms of the landing phase was that the effect of WR was non-significant ($P > 0.05$) on peak GRF. With regards to the propulsive phase the main findings were that for both the CMJ and DJ, WR resulted in a significant ($P < 0.05$) decrease in jump height (CMJ: -12 to -17%, DJ: -10 to -14%); relative peak power (CMJ: -8 to -17%, DJ: -7 to -10%); and peak velocity (CMJ: -4 to -7%, DJ: -3 to -8%); while PJ reactive strength index was significantly reduced (-15 to -21%) with all WR conditions. Consideration should be given to the inclusion of WR in sports where VJ's are important components as it may provide a novel movement specific training stimulus.

Appendix I. Publication: Effects of upper and lower body wearable resistance on spatio-temporal and kinetic parameters during running

This appendix comprises the abstract for the following publication in *Sports Biomechanics,* which was referenced in Chapter 5 and which KS was a research supervisor and co-author for during the period of PhD enrolment:

Couture, G. A., Simperingham, K. D., Cronin, J. B., Lorimer, A. V., Kilding, A. E., & Macadam, P. (2018). Effects of upper and lower body wearable resistance on spatio-temporal and kinetic parameters during running. *Sports Biomechanics*, 1-19.

Wearable resistance training involves added load attached directly to the body during sporting movements. The effects of load position during running are not yet fully established. Therefore the purpose of this research was to determine spatiotemporal and kinetic characteristics during submaximal running using upper-, lower- and whole-body wearable resistance (1-10% body mass (BM)). Twelve trained male runners completed eight two min treadmill running bouts at 3.9 m/s with and without wearable resistance. The first and last bouts were unloaded, while the middle six were randomised wearable resistance conditions: upper-body (UB) 5% BM, lower-body (LB) 1, 3, 5% BM, and whole-body (WB) 5, 10% BM. Wearable resistance of 1-10% BM resulted in a significant increase in heart rate (5.4-8.8%), but minimal impact on spatiotemporal variables. Loads of 5% BM and greater caused changes in vertical stiffness, vertical and horizontal force, and impulse. Functional and effective propulsive force (3.0%, 2.8%) and impulse (2.9%, 3.5%) were significantly ($p < 0.05$) greater with LB5% than UB5%. Wearable resistance may be used to increase forces and muscular stimulus without negatively impacting running. The application of these findings will vary depending on athlete goals. Future longitudinal studies are required to validate training contentions.

Appendix J. Publication: Forearm wearable resistance effects on sprint kinematics and kinetics

This appendix comprises the abstract for the following publication in *Journal of Science and Medicine in Sport*, which was referenced in Chapter 5 and which KS was a research supervisor and co-author for during the period of PhD enrolment:

Macadam, P., Simperingham, K. D., & Cronin, J. B. (2019). Forearm wearable resistance effects on sprint kinematics and kinetics. *Journal of Science and Medicine in Sport, 22*(3), 348-352.

Objectives: Arm swing is a distinctive characteristic of sprint-running with the arms working in a contralateral manner with the legs to propel the body in a horizontal direction. The purpose of this study was to determine the acute changes in kinematics and kinetics when wearable resistance (WR) of 1 kg (equivalent to ~1% body mass) was attached to each forearm during over-ground short distance (20 m) maximal sprint-running.

Design: Cross-sectional study.

Methods: Twenty-two male amateur rugby athletes (19.4 ± 0.5 years; 97.0 ± 4.8 kg; 180.4 ± 7.2 cm) volunteered to participate in the study. Radar and Optojump were used to examine kinematic and kinetics between WR and unloaded sprint-running conditions.

Results: No significant ($p < 0.05$) differences were found at 2 m or 5 m between conditions, however, the WR condition resulted in a significant decrease in 10 m, 20 m and 10-20 m split time (all ~ -2%, small effect size) compared to the unloaded condition. Significant decreases were also found in theoretical maximum velocity (V0) (-1.4%, small effect size) and relative peak horizontal power production (Pmax) (-5.5%, small effect size). Step length (2.1%, small effect size) and contact time (6.5%, medium effect size) were significantly increased, while step frequency (-4.1%, small effect size) and flight time (-5.3%, medium effect size) were significantly decreased.

Conclusions: WR forearm loading provides a movement specific overload of the arms which significantly alters step kinematics and sprint times ≥ 10 m.

Appendix K. Publication: Acute kinematic and kinetic adaptations to wearable resistance during sprint acceleration

This appendix comprises the abstract for the following publication in *Journal of Strength and Conditioning Research,* which was referenced in Chapter 5 and which KS was a research supervisor and co-author for during the period of PhD enrolment:

Macadam, P., Simperingham, K. D., & Cronin, J. B. (2017). Acute kinematic and kinetic adaptations to wearable resistance during sprint acceleration. *Journal of Strength and Conditioning Research, 31*(5), 1297-1304.

Wearable resistance (WR) in the form of weighted vests and shorts enables movement specific sprint running to be performed under load. The purpose of this study was to determine the acute changes in kinematics and kinetics when an additional load equivalent to 3% body mass (BM) was attached to the anterior or posterior surface of the lower limbs during sprint running. Nineteen male rugby athletes (age: 19.7 ± 2.3 years; body mass: 96.1 ± 16.5 kg; height: 181 ± 6.5 cm) volunteered to participate in the study. Subjects performed six 20 m sprints in a randomized fashion wearing no resistance or 3%BM affixed to the anterior (quadriceps and tibialis anterior) or posterior (hamstring and gastrocnemius) surface of the lower limbs (two sprints per condition). Optojump and radar were used to quantify sprint times, horizontal velocity, contact and flight times, and step length and frequency. A repeated measures analysis of variance with post hoc contrasts was used to determine differences ($p \leq 0.05$) between conditions. No significant differences were found between the anterior and posterior WR conditions in any of the variables of interest. There was no significant change in sprint times over the initial 10 m, however the 10 to 20 m split times were significantly slower (-2.2 to -2.9%) for the WR conditions compared to the unloaded sprints. A significant change in the relative force-velocity (*F*-*v*) slope (-10.5 to -10.9%) and theoretical maximum velocity (V0) (-5.4 to -6.5%) was found, while a non-significant increase in theoretical maximum force (F0) (4.9 to 5.2%) occurred. WR of 3%BM may be a suitable training modality to enhance sprint acceleration performance by overloading the athlete without negatively affecting sprint running technique.

Appendix L. Conference Presentation: Changes in acceleration phase sprint biomechanics with lower body wearable resistance

This appendix comprises a subset of the data included in Chapter 8 of this thesis, and was presented at *the 34th International Conference of Biomechanics in Sport* (Tsukuba, Japan):

Simperingham, K. D., Cronin, J., Pearson, S., & Ross, A. (2016). *Changes in acceleration phase sprint biomechanics with lower body wearable resistance*. presented at the meeting of the 34th International Conference of Biomechanics in Sport, Tsukuba, Japan.

CHANGES IN ACCELERATION PHASE SPRINT BIOMECHANICS WITH LOWER BODY WEARABLE RESISTANCE

Kim Simperingham[1,3], John Cronin[1,2], Simon Pearson[1,3] and Angus Ross[1,3]

Sports Performance Research Institute New Zealand, AUT University, Auckland, NZ[1]
School of Exercise, Biomedical and Health Sciences, Edith Cowan University, Australia[2]
High Performance Sport New Zealand, Auckland, New Zealand[3]

Wearable resistance (WR) attached to the lower body may be advantageous for sprint acceleration training. The aim of this study was to quantify the kinematic and kinetic changes that occur during the sprint acceleration phase when lower body WR is worn. Radar and Optojump were used to assess fifteen male rugby athletes sprinting over 20 m under three different loading conditions: 0%, 3% and 5% body mass added weight attached to the lower body. Moderately loaded WR (3% BM) resulted in higher horizontal force and horizontal power outputs compared to heavier loading during the acceleration phase. Sprint acceleration biomechanics were minimally affected by WR loading up to 5% BM.