Understanding Rotational Overload Effects of Thigh Wearable Resistance on Kinematic and Kinetic Properties of Sprint-Running

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Abstract

Advancements in technology enable loads to be attached on the body, creating wearable resistance (WR) which athletes can wear during sport-specific movements, such as sprint-running. Measurements of sprint-running mechanics are often linear in quantification, despite being the result of joint rotations. Therefore, quantifying rotational movement, especially with the emergence of WR limb loading is important. One measurement tool that can collect rotational movement data is an inertial measurement unit (IMU) which allows sprint performance to be measured within its natural context. This research aimed to assess the kinematic and kinetic effects of a sprint-specific rotational form of resistance through thigh attached WR and sought to determine whether IMUs could quantify rotational kinematics of sprint-running.

A review into the effects of leg attached WR on sprint-running performance found WR of ≤5% body mass (BM), provided a significant overload to step frequency while having minimal impact on step length. However, no studies had assessed the rotational work of the thighs and limited research had investigated kinetic changes. A review investigating the use of inertial sensors during sprint-running found mixed levels of agreement, mainly due to the methodological differences. Moreover, the use of inertial sensors to quantify rotational kinematics had not been investigated. The identified gaps and limitations from the reviews set the framework for the thesis.

The first study determined if IMUs could quantify thigh rotational kinematics during sprint-running. The IMU derived thigh angular displacement and velocity were reproducible between trials (coefficient of variation 6.7-9.7%, intraclass correlation coefficient: 0.95-0.96). Compared to a motion capture system, moderate to high levels of agreement were found, with the IMU underestimating thigh angular displacement (-6.7% to -9.0%) and angular velocity (-5.3% to -16.4%). Study two determined the load effects of thigh WR on kinematics and kinetics during non-motorised treadmill sprinting. Thigh WR ≥2% BM resulted in moderate to large effect size (ES) changes (-7.0% to -12.0%) in angular kinematics with trivial to small ES changes (-3.6% to 5.0%) found in linear kinematic and kinetic sprint-running properties.

Given greater changes found with WR ≥2% BM, studies three to five used 2% BM. Study three assessed changes in kinematics and kinetics, and study four quantified mechanical rotational changes, both during 50 m over ground sprint-running. The WR condition resulted in small ES increases (<2%) in sprint times, moderate ES changes in net anterior-posterior impulses (-4.8%), vertical stiffness (-5.7%), and step frequency (-2.8%) while step length was unaffected. The rotational changes were trivial to small ES increases in thigh angular displacement (0.6-3.4%), a significant decrease in thigh angular velocity (-2.5% to -8.0%), and rotational work was significantly increased (9.8-19.0%). The fifth study measured the effects of thigh WR on sprint-

running performance following a 5 week training period using a single-subject design. Thigh WR resulted in increased horizontal force (7.1%), vertical stiffness (12.9%) and rotational thigh velocity (4.5%) resulting in faster times (2.4-3.4%) over 40 m sprint-running.

In summary, thigh WR provided similar effects to previous WR research in linear kinematic and kinetic properties. By utilising IMUs to investigate rotational movement specific loading, this thesis provided original research into the significant changes in rotational kinematics and work from thigh WR which provided a more ecological valid measure of sprint-specific rotational training. As such, rotational overloading of the hip musculature can be achieved in a progressive and planned manner, which assists with WR programming for improved sprint performance.

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Attestation of Authorship

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

Paul Macadam 7/3/2020

Co-Authored Works

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

Chapter 2	The effects of different wearable resistance placements on sprint-running performance: a review and practical applications. Strength and Conditioning Journal, 41 (3), 79-96. doi: 10.1519/SSC.0000000000000444 Macadam 85%, Cronin 6%, Uthoff 5%, Feser 4%
Chapter 3	Quantification of the validity and reliability of sprint performance metrics computed using inertial sensors: a systematic review. Gait & Posture Journal, 73, 26-38. doi: 10.1016/j.gaitpost.2019.07.123 Macadam 85%, Cronin 8%, Diewald 4%, Neville 3%
Chapter 4	Can inertial measurements units quantify thigh rotational kinematics during sprint-running? Journal of Measurement in Physical Education and Exercise Science (In Review) Macadam 80%, Cronin 4%, Nagahara 3%, Wells 3%, Uthoff 2%, Graham 2%, Diewald 2%, Kameda 2%, Neville 2%
Chapter 5	Load effects of thigh wearable resistance on angular and linear kinematics and kinetics during non-motorised treadmill sprint-running. European Journal of Sport Science. doi: 10.1080/17461391.2020.1764629 Macadam 85%, Nuell 4%, Cronin 4%, Diewald 3%, Forster 2%, Fosch 2%,
Chapter 6	Thigh positioned wearable resistance affects step frequency not step length during 50 m sprint-running. European Journal of Sport Science, doi: 10.1080/17461391.2019.1641557 Macadam 80%, Nuell 5%, Cronin 5%, Nagahara 2%, Uthoff 2%, Tinwala 2%, Graham 2%, Neville 2%
Chapter 7	Thigh loaded wearable resistance increases sagittal plane rotational work of the thigh resulting in slower 50 m sprint times. Sports Biomechanics Journal. doi: 10.1080/14763141.2020.1762720 Macadam 80%, Cronin 4%, Nagahara 3%, Zois 3%, Uthoff 3%, Diewald 3%, Tinwala 2%, Neville 2%

Chapter 8 Thigh positioned wearable resistance improves 40 m sprint performance: a longitudinal single case design study. Journal of Australian Strength & Conditioning. 27(4), 39-45

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Ethics Approval

Ethical approval was granted by the Auckland University of Technology Ethics Committee (AUTEC) - Ethics Application: 15/07 Light variable resistance training with Exogen exoskeletons. Ethics were obtained prior to the beginning of this thesis. This approval provides the ability of collect data which may be utilised in research studies such as those completed in this thesis. Amendments to Ethics were made when required and are presented in Appendix I.

Chapter 1. Introduction

1.1 Background

Sprint-running performance is essential for individual and team sport athletes. Recent advancements in sports technology allow loads to be attached on the torso or limbs, creating wearable resistance (WR) which athletes can wear during sport-specific movements, such as sprint-running. Fundamental understanding of sprint-running mechanics is often linear in quantification, i.e. split times, distance travelled, high speed metres, etc. The same is true of typical force plate research, which give measures of linear kinetic variables such as force, power, or impulse. These linear outcome measures are the result of rotation at the joints and therefore finding ways to quantify rotational movement would seem important, especially with the emergence of WR limb loading. One measurement tool that can collect a large amount of rotational movement data is an inertial measurement unit (IMU) which allows sprint performance to be measured within its natural context. Of importance for coaches, and strength and conditioning practitioners is: 1) how to progressively overload athletes to improve sprint performance without increasing injury risk; and, 2) how best to evaluate and monitor sprint-running performance. Therefore, the specific aims of this research are to determine the kinematics and kinetic effects of a sprint-specific rotational form of overloading through thigh attached WR, and to assess whether IMUs can quantify sagittal plane rotational kinematics during sprint-running.

Lila™ Exogen™ exoskeleton will be used for WR loading, attached to the distal aspect of the thigh. The Lila™ Exogen™ exoskeleton form of WR loading was chosen it has improved attachment issues, specifically for light WR, enabling limb specific rotational loading unlike other forms of WR. The thesis findings will inform athletic sprint-running testing and training procedures and potentially provide an athlete-specific method of determining rotational mechanical workload changes from inertial sensors. Furthermore, this project will help contribute to the smart fitness movement, as athletes continue to strive towards to quantification of performance and data-driven training. The introduction of a portable tool that can monitor sprint-running performance will allow biomechanical research to expand beyond laboratory conditions, where sprint-running environments are often imitated, and into a more natural environment. The following sections discuss the previous literature related to the two areas of this thesis: 1) the effects of lower-limb WR during running and sprint-running; and, 2) measurements of sprint-running performance from inertial sensors.

1.1.2. The Effects of Lower-Limb Wearable Resistance during Running and Sprint-Running

To enhance sprint-running performance, athletes often undertake various forms of complementary training such as resistance training (RT), plyometric training, mobility work, and several forms of cross training. RT is widely used by athletes both for injury prevention (138) and to improve the physical features related to performance such as leg strength and power (12, 56, 63, 109) and leg stiffness (58, 68, 71). There are several effective RT methods, each with their own advantages and disadvantages to improve sprint-running performance including: 1) heavy load training (84); 2) plyometrics and explosive training (109, 124, 125); and, 3) high-intensity interval training (48). Recently, there has been a focus on the effectiveness of sport-specific RT strategies, allowing athletes to achieve the benefits of RT during sprint-running itself. One such form of sport-specific RT is WR which involves a load being directly attached to the body via a garment worn during sporting movements (73). This form of training incorporates an added load but facilitates sport-specific movement through the full range of motion. This specificity of movement can promote intermuscular coordination which has been shown to increase transference to sport performance (156).

Previous WR studies have used loads attached to the trunk or limbs during running and sprint-running with loads ranging from 0.3% to 40% body mass (BM) (72, 73). It has been documented that additional mass added to the body increases the workload required for locomotion (20, 139). According to the rotational component of Newton's second law of motion, the torque required to create angular acceleration is proportional to the moment of inertia of the object (the leg and mass), which is exponentially related to the radius from the axis (hip joint). Hence, as a load is placed more distally on the limb, the torque necessary to accelerate the limb will increase exponentially. As more torque is required during each step with limb loading, the leg muscles must generate more force, and thus expend more rotational mechanical work, for a given rate of limb movement when rotational displacement is maintained. Previous research has documented increases in work expenditure due to limb loading of the foot or ankle during running (40, 52, 62, 80, 94). Though some researchers have proposed that oxygen consumption increases by between 0.9-1.5% for every additional 100 gram on each foot, Franz, et al. (52) summarised these findings and found that only two of seven studies found a difference of that proportion. Therefore, the workload effects of lower-limb WR are yet to be clearly established. Though multiple loading positions for WR are available, the following section summaries the findings of WR attached to the thigh only.

The importance of understanding thigh attached WR may relate to findings by Dorn, Schache and Pandy (43) who found that at faster speeds (>7.0 m/s) higher step frequencies were produced, which resulted from large hip angular velocities in the swing phase, highlighting the importance of hip musculature affecting step frequency. Therefore, training methods that overload the hip musculature, and thus step frequency during sprint-running, may lead to beneficial performance changes. Although several studies have investigated the effects of WR on the ankle, foot or whole leg loading, only three studies have examined the effects of WR attached only to the thigh musculature at running speeds (80, 81, 94). Two studies (80, 81) investigated the effects of mid to upper thigh loading during 10 minutes of treadmill running at 3.3 m/s. Thigh loads of 0.5 kg and 1.0 kg (0.6% and 1.4% BM) resulted in significantly increased maximum oxygen uptake of 1.7% and 3.5%, respectively; however, the loads did not significantly change any kinematic variables of interest (stride length: 0-0.3%, contact time: 0-0.4% and flight time -1.1% to 3.2%) (80), while no kinetic measures were reported. Workload was significantly increased (9.5%) with 1.4% BM WR but smaller increases (2.5%, $p > 0.05$) were found with 0.6% BM WR (80). No significant changes were found in joint reaction forces with either WR magnitude (81). The third study also assessed treadmill running (2.7 m/s) until oxygen consumption levelled but with a greater magnitude of WR 3.6 kg (4.8-5.8% BM) placed on the upper area of the thigh via a belt with added lead pellets which significantly increased (9.4%) energy consumption (converted from oxygen consumption based on respiratory quotient) (94). Mechanical work and net metabolic rate measured with thigh loads may reflect both the addition of the load and frontal plane alterations in gait with net metabolic rate increasing when step width and lateral leg circumduction are increased (42). These factors are highlighted by the placement and attachment methods used in the three studies. The load placement used in the three running studies differed between subjects due to anthropometric characteristics with the average placement approximately 68% of thigh length from the hip joint centre (range 59-80%) (80, 81) while the placement by Myers and Steudel (94) was reported as the upper thigh. As can be observed there are no systematic trends in the results related to the effect of thigh attached WR on rotational mechanical workload. This can be attributed in part to: 1) magnitude of loads (0.6 to 5.8% BM); 2) placement of loads (proximal to mid-femur) which effects rotational inertia; 3) the different methodologies used (work load calculations); and, 4) the duration and speeds of the running phase investigated.

Regarding sprinting with WR, three recent acute studies that used whole leg WR of 2.4-3% BM (13, 77, 136) found significant decreases in step frequency (-1.3% to -3.6%), though step length was minimally changed (-0.6% to 0.8%, $p > 0.05$), and increases of 2-4% ($p < 0.05$) in contact time and 5-6% ($p > 0.05$) in horizontal force production, Therefore, it could be suggested this form of training may be a potential method to improve sprint performance due to overloading step frequency without changing step length. However, from changes to linear kinematic and kinetic properties, the effect size (ES) changes with whole leg WR have been trivial to moderate. Therefore, greater changes may be occurring in the rotational action of the legs, though no studies have investigated the rotational effects of WR. Moreover, only one WR training study has been completed which used 5% BM ankle WR and was found to elicit a significantly increased stride length (5.3%) and decreased stride frequency (-5.6%) as measured between 25 m and 50 m with no significant changes to maximal running speed. Given these acute changes, and only one longitudinal leg WR study, further research is required to assess potential sprint-running performance improvements.

From the above limited research, differences in WR magnitude and placement, workload calculation methods, and locomotion speeds make it difficult to quantify how changes in WR attached to the thigh affect the mechanical rotational workload variables during running and sprint-running. Moreover, no research into the effects of thigh loaded WR on rotational work has been completed since 1990, hence this area may benefit from modern technology and methodological processes. Any increase in net metabolic rate during sprint-running with an external load would, presumably, be accompanied by changes in the mechanical determinants of metabolic rate due to greater inertia. However, research is required to investigate this contention. As greater changes were found in a more distal placement through foot and ankle loading, future research should investigate WR placed distally on the thigh as the three thigh WR studies in this review placed WR on either the upper or middle aspect of the thigh segment. Given the greater morphology of the thigh segment and the importance of the hip musculature in horizontal force production during sprint-running (89), WR positioned distally on the thigh warrants investigation.

1.1.3. Measurements of Sprint-running Performance from Wearable Inertial Sensors

The popularity of sprint-running in both recreational settings and in sport training and competitive games has encouraged a considerable body of research and assessment (32, 35, 81, 87). This has been potentiated by advances in technology including faster frame rate cameras, wearable inertial sensors, force plates, improved motion capture analysis and computer modelling systems. Though motion capture is the current gold standard reference system for motion analysis (28), this system is not portable, has a limited capture volume and requires a trained technician to collect and analyse the data. Therefore, wearable inertial sensors, such as an IMU have been proposed as a means to address most of the aforementioned limitations (69). Accurately capturing and analysing kinematic data (joint angles, velocities, and accelerations) is of great importance to practitioners as the information provides a great deal of insight into locomotion performance and irregularities (96, 146). The association between workload, fatigue and injury are common issues faced by athletes and practitioners. Therefore, understanding how to accurately quantify these factors and use that information to enhance training for optimal performance is of great importance. An IMU can measure linear and angular motions in three-dimensional space without external references. Often comprised of a 3-axis accelerometer, 3-axis gyroscope, and a 3-axis magnetometer, or a combination, these sensors are able to obtain the orientation and movement of a body or a segment of the body (49). Accelerometers are used to measure acceleration and tilt and thus in many situations can be used to calculate a gravity vector (orientation), gyroscopes are used to measure angular velocity, and magnetometers help provide global orientation and direction information. Advances in microelectromechanical systems have enabled these light, low cost, and low power body mounted sensors to be a more practical option compared to laboratory-based equipment. By applying signal processing methodologies to the raw data from the IMU, kinematic parameters of locomotion can be reliably measured and a sensor fusion algorithm can be used to accurately track the IMU's orientation over time (50).

Recently, studies have used wearable inertial sensors to measure performance and rotational kinematic metrics during running and sprint-running. With wearable inertial sensors (IMUs or accelerometers) attached to the thigh, kinematic data relating to the hip joint has been quantified during treadmill and over ground running speeds (116, 141, 153) and sprinting speeds (142, 143). Wearable inertial sensors were able to detect greater hip joint range of motion at sprinting speeds (89.1 ± 3.3°) (142) compared to running speeds (49.7-55.7 ± 0.7-7.2°) (116, 141, 142). The sensors were also able to detect angular velocity of the thigh which was significantly decreased (4.5%) during the over the ground run compare to treadmill run (141) possibly due to the changing over ground surface compared to a constant treadmill belt. Only Nüesch, Roos, Pagenstert and Mündermann (108) have validated rotational kinematic values from a thigh placed IMU compared to motion capture with a mean hip angle correlation of 0.54 found during treadmill running. A review into wearable sensors during running suggests that placement of sensors closest to the area of interest along with the use of bi/tri-axial accelerometers appear to provide the most accurate results (105). However, as only one study has reported validity measures of rotational kinematics with thigh placed IMUs during treadmill running, further research is needed. Application of IMU usage is still underutilised in research possibly due to the lack of standards for sensor specifications, sensor placements and definite joint coordinate systems which limits the correct joint kinematic calculations (148). Furthermore, differences between the placement of the wearable sensor, type of sensor, running surface and running speeds have resulted in mixed validity findings when compared to referenced systems (14, 70, 141).

The accuracy of the orientation estimation can be affected by calibration stages of the individual sensors (i.e., accelerometer, gyroscope, and magnetometer), diverse noise types, and sensor fusion algorithm issues (148). Therefore, further research is needed to validate wearable inertial sensors with the current gold standard reference systems. By designing a system using IMU technology and verifying the model through extensive testing, a wearable inertial sensor can replace current laboratory-based testing equipment and could revolutionise the way rotational movement (e.g. running and sprint-running) training is directed. This system offers a low-cost opportunity for athletes to monitor their rotational movement and improve their technique in a way that could help improve performance and reduce the risk of injury. The introduction of a portable tool that can monitor rotational movement will allow biomechanical research to expand beyond laboratory conditions, where the running environments are often imitated, and into more natural running environment. Furthermore, a more flexible data collection could be conducted with the ability to test multiple subjects without the usual restrictions of motion capture technology. Additional metrics such as cadence (steps/minute) and impact (force at which the runner hits the ground) can be added into the system using the IMU data. Overall, further developing this system could help contribute to the smart fitness movement, as athletes continue to strive towards to quantification of performance and data-based training.

1.2 Rationale and Significance of the Study

Loading of lower limbs has received limited research to date, with only three studies examining the effects of WR limb-loads attached to the thigh musculature. Moreover, these studies were all conducted using a motorised treadmill at running speeds of $\leq$ 3.3 m/s. Furthermore, though whole leg WR has been found to change linear kinematic and kinetic properties of sprint-running, notably step frequency and contact times, the rotational effects of WR are unknown. The importance of understanding sprint-running rotational movement via thigh loading, through mechanical rotational workload responses may assist practitioners in monitoring training loads, which subsequently may reduce excessive training overload. Moreover, through quantifying a movement specific form of training through the addition of WR, practitioners may be assisted in planning appropriate loading for an athlete’s training program.

Though measurement of kinematic and kinetic parameters during running and sprint-running can be acquired through laboratory-based equipment (force plate technology and motion capture systems), by additionally utilising IMU data collection, a more direct and practical measure of rotational movement parameters can be collected. By utilising wearable sensor technology to monitor and evaluate movement specific loading using WR, this thesis provides original scientific research into rotational kinematics and work which may be beneficial for practitioners in providing a more ecological valid measure of sprint-specific rotational training.

1.3 Research Question

As WR has been found to overload linear kinematic and kinetic properties of sprint-running performance, understanding the rotational effects of distally placed thigh WR, coupled with the linear effects, requires investigation. Therefore, the overarching question of this thesis is "What are the rotational overload effects of thigh wearable resistance on kinematic and kinetic properties of sprint-running?"

To answer this question, two areas will be investigated:

1) What are the acute and longitudinal linear and rotational overload effects of thigh WR on kinematics and kinetics during sprint-running?
2) Can IMUs be used to quantify thigh rotational kinematics during sprint-running?

1.4 Thesis Organisation

The thesis is structured into four sections which are summarised in Figure 1. The thesis consists of two literature reviews (Chapters 2 and 3) and five investigations (Chapters 4-8), all of which have been published, or are in review for publication with international peer-reviewed journals to fulfil the Format Two thesis requirements. As such, each chapter has been adapted from a published or submitted version to ensure the thesis reads as a cohesive whole. For consistency, all referencing is in a numerical system based on the Strength and Conditioning Journal format, with a single citation summary presented at the end of the thesis.

Section one addresses gaps in the current body of literature regarding the effects of WR on sprint-running performance. In addition, the current body of literature regarding IMU utilisation for collecting and quantifying sprint-running performance measures are discussed. Section two establishes if IMUs can be used to quantify rotational kinematics during sprint-running. Section three quantifies the effect of WR on linear kinematics and kinetics and rotational kinematics and workload during sprint-running from acute and longitudinal studies. The final chapter includes a summary of the resulting original contributions to knowledge in the context of past literature and will also explain the limitations of the thesis findings and suggestions for future research. The appendices present all relevant material from the studies including Ethical Approval, Participant Information Sheets and Informed Consent Forms, and Abstracts from the Chapters. Please note that there is some repetition throughout the thesis owing to the format in which the overall thesis is presented, that is, thesis by publication.

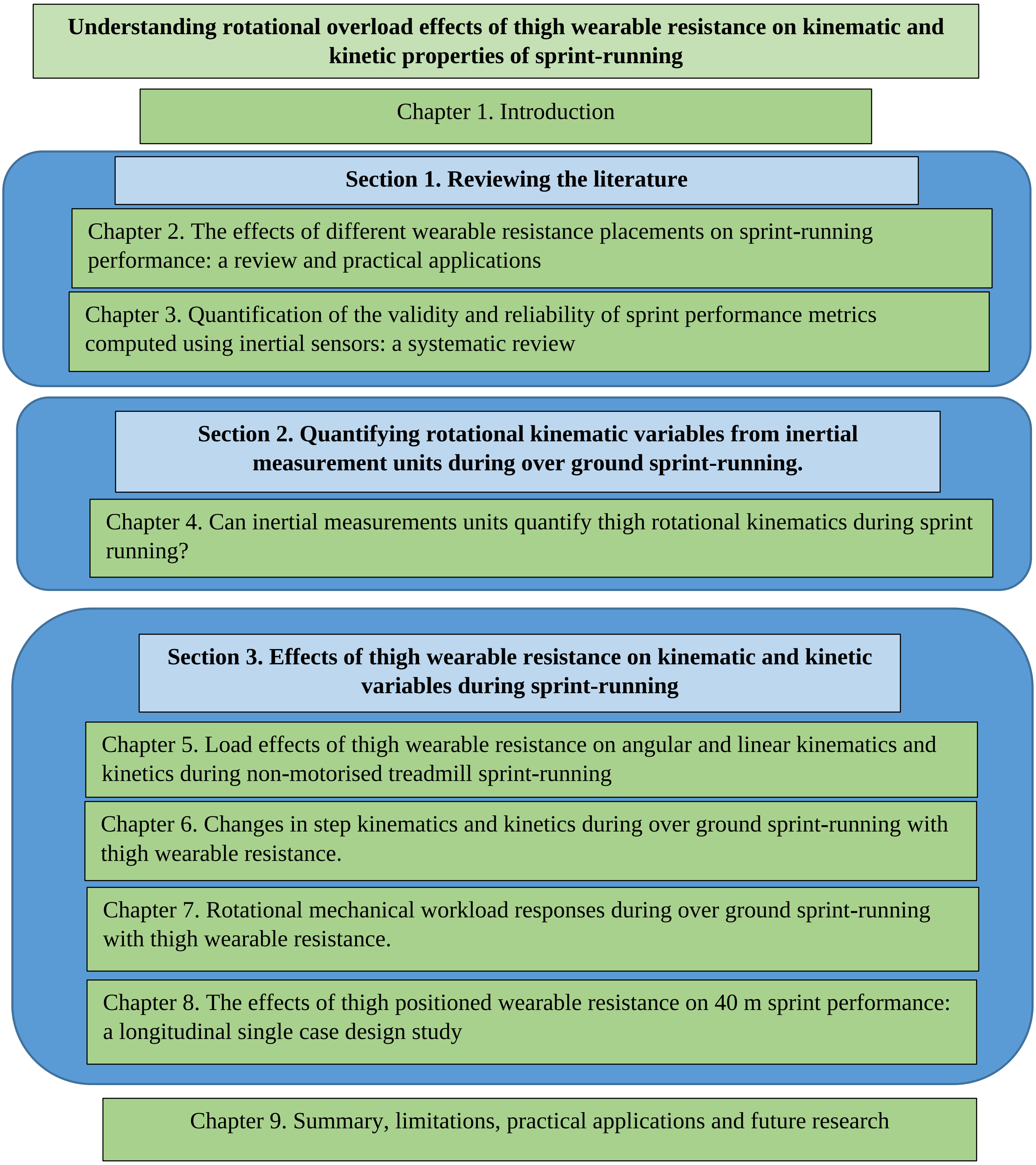


Figure 1. Thesis Structure.

Section 1. Reviewing the Literature

Chapter 2. The Effects of Different Wearable Resistance Placements on Sprint-Running Performance: A Review and Practical Applications

Chapter 3. Quantification of the Validity and Reliability of Sprint Performance Metrics Computed Using Inertial Sensors: A Systematic Review

This section reviewed the current literature regarding the effects of WR on sprint-running performance and how the differences between WR placements, i.e. trunk, legs and arms, may affect sprint-running performance. In addition, this section contains a systematic review into the validity and reliability of wearable inertial sensor technology for quantifying sprint-running performance metrics compared to the current referenced systems.

Chapter 2. The Effects of Different Wearable Resistance Placements on Sprint-Running Performance: A Review and Practical Applications

This chapter comprises the following paper published in the Strength and Conditioning Journal.

Reference: Macadam, P., Cronin, J., Uthoff, A, Feser, E. (2019). Effects of different wearable resistance placements on sprint-running performance: a review and practical applications. *Strength and Conditioning Journal*, *41*(3), 79–96. doi: 10.1519/SSC.0000000000000444.

Author contributions: Macadam 80%, Cronin 10%, Uthoff 5%, Feser 5%

2.0 Prelude

To enhance sprint-running performance, athletes often undertake various forms of complementary training such as resistance training, plyometric training and several forms of cross training. Resistance training is widely used by athletes both for injury prevention and recovery, and to improve the physical and physiological features related to performance such as speed, strength and power. Recently, there has been a focus on the effectiveness of sport-specific resistance training strategies, allowing athletes to achieve the benefits of resistance training during specific actions that mimic their sport itself. One such form of sport-specific training is WR which involves a load being directly attached to the body, via a garment, worn during sporting movements and facilitates training of sport-specific movements such as sprint-running. Therefore, the purpose of this chapter was to review the literature to date regarding the effects of WR on sprint-running performance and how different placements may affect different measures of sprint performance. The reported outcomes will provide a basis for examining the impact of WR placements during sprint-running in the subsequent studies.

2.1 Introduction

Sprint-running, and the ability to accelerate over short distance, is a key component of performance for many sports. Understanding the specific mechanical determinants of sprint-running and finding methods to train these factors is pivotal for practitioners in designing programs and optimising adaptation. Though traditional gym-based resistance training is frequently utilised to improve force production, questions remain whether this form of training is optimum for transferring strength gains to sprint-running performance. Although, some literature reviews have found that resistance training was an effective means to improve sprint performance (18, 131), other reviews have indicated that it is less effective compared to simply performing sprint training (33, 122).

The suspected lack of transfer of gym based resistance training to sprint-running performance may be due to: 1) the bilateral exercises performed in the gym are unlike sprint-running which principally involves unilateral propulsion; 2) exercises are vertically oriented while horizontal and lateral force production are often under-trained, even though vital components of speed are associated with these force directions; 3) exercises lack velocity and full range of motion specificity to sprint-running; 4) exercises tend to be acyclic whereas field movement is cyclic; and, 5) exercises are often uni-planar whereas field based movement is typically multi-planar. Transference, at its essence, is the goal of the practitioner when developing a resistance training program. Therefore, adapting methodologies that develop aspects of an athlete’s speed qualities relative to the sport is critical. Though external loading via traditional gym resistance training (free weights, machines, etc.) have progressed certain aspects of our movement knowledge and ability, they present the practitioner with the formidable challenge of transferring non-specific strength gains to improved sprint performance in the field.

As practitioners seek to find methods to optimise sprint-running performance, WR is one modality that enables athletes to perform movement-specific resisted training (73). This form of training aligns with the concept of specificity, which has been promoted as an important factor when prescribing sprint training programs (32). This Chapter reviews the literature regarding the effects of WR on sprint-running performance and explores how differences in WR placements may affect sprint-running performance. The potential benefits of WR will be presented, as well as the loading schemes that optimise adaptation. Peer-reviewed journal articles and conference papers were retrieved from electronic searches of Science Direct, Web of Science, PubMed, Google Scholar and SPORTDiscus databases, in addition to relevant bibliographic hand searches with articles limited to English language. The search strategy included the terms wearable resistance, weighted vest, limb loading, trunk loading, external loading, resisted sprinting, inertia loading, added mass, sprint, acceleration and velocity. The month of the last search performed was September 2018. A total of twenty studies met the inclusion criteria for this review.

2.2 Wearable Resistance Usage During Sprint-Running

To date, twenty studies have utilised WR during sprint-running (Table 1). The customisability of WR has enabled multiple attachment positions on the body: ankle, shank, thigh, trunk, and arm. These positions are summarised into Tables 2-4 representing arms (Table 2), trunk (Table 3) and legs (Table 4). Moreover, three leg WR studies quantified the acute enhancement effects on sprint-running which can be found in Table 5. A summary of the effects on sprint performance with WR from all positions during the acceleration phase, can be found in Table 6, and during the maximum velocity phase, in Table 7. A diverse subject pool has been used for WR studies, ranging from sedentary subjects, to sport-based students to national rugby players and national beach sprinters. Both acute and longitudinal studies have used WR, with the effects quantified from over ground sprint distances ranging from 10 m to 50 m, and 6 seconds of sprint-running on a non-motorised treadmill. The magnitude of WR has ranged from as little as 0.6% BM to 21.8% BM. Reasons for this loading range relate to differences in body surface areas, enabling greater loads to be attached to the trunk (5-21.8% BM), while due to the smaller surface areas, lighter loads have been utilised with arm (≤ 2.5% BM) and leg (≤ 5% BM) placements.

Table 1. Summary of all wearable resistance sprint-running studies (n = 20).

Study	Subjects	WR placement	WR magnitude (% body mass)	Sprint protocol	Study duration
Ropret et al. (119)	24 males, 20.1 ± 0.9 years, 179.6 ± 8.4 cm, 74.5 ± 9.8 kg Physical education students	Hand Ankle	0.6, 1.2, 1.8 1.6, 3.2, 4.8	30 m	Acute
Cronin et al. (31)	16 males, 4 females, 19.9 ± 2.2 years, 176 ± 8 cm, 76.5 ± 10.7 kg Competitive athletes from mixed sports	Trunk	15 20	30 m	Acute
McNaughton & Kelly (82)	10 males, 26.3 ± 5.1 years Team sport athletes	Forearm	1 kg	40 m	Acute
Bennett el al. (13)	8 males, 26.0 ± 7.3 years, 177.3 ± 3.4 cm, 77.3 ± 3.9 kg National level beach sprinters	Whole leg	2.4	40 m	Acute and Acute enhancement
Clark et al. (26)	6 males, 19.7 ± 0.1 years, 182 ± 8 cm, 79.1 ± 5.3 kg NCAA Division 3 lacrosse players	Trunk	18.5	55 m	7 weeks
Pajić et al. (110)	6 individuals per group, gender not specified, 20.4 ± 1.7 years, 178.4 ± 8.12 cm, 71.4 ± 8.5 kg Physical education students	Arms Ankle	2.5	50 m	6 weeks
Rantalainen et al.	8 males, 32.2 ± 6.4 years,	Trunk	5.6	10 m	3 weeks

(115)	178 ± 5 cm, 81.8 ± 8 kg Sedentary subjects				
Cross et al. (36)	13 males, 22.9 ± 3.3 years; 179 ± 6 cm, 82.5 ± 8.4 kg Sport active university level athletes	Trunk	10.9 21.8	6 s sprint, non-motorised treadmill	Acute
Konstantinos et al. (65)	24 males, 18–23 years, 178 ± 5 cm, 74.2 ± 8.9 kg Sport science students	Trunk	5 10 15	50 m	Acute
Simperingham & Cronin (134)	8 males, 29.2 ± 3.8 years, 177.1 ± 7.5 cm, 81.8 ± 9.7 kg Athletic team sports based	Whole leg Trunk	5	6 s sprint, non-motorised treadmill	Acute and Acute enhancement
Barr et al. (9)	8 males, 22.4 ± 2.7 years 182 ± 6 cm, 95.3 ± 7.1 kg National rugby players	Trunk	12	40 m	8 days
Simperingham et al. (135)	1 male, 29.2 years, 180.8 cm, 87.2 kg Rugby union athlete	Whole leg	1, 3, 5	40 m	Acute enhancement
Scudamore et al. (130)	9 males, 21 ± 2 years, 181 ± 1 cm, 91.1 ± 4.4 kg Fitness active subjects	Trunk	Week 1 - 11.2 Week 2 - 13.2 Week 3 - 16.1	36.6 m	3 weeks
Simperingham et al. (136)	15 males, 19.0 ± 0.5 years 181.2 ± 7.3 cm, 91.0 ± 17.4 kg Rugby union athletes	Whole leg	3 5	20 m	Acute
Macadam et al. (77)	19 males, 19.7 ± 2.3 years, 181 ± 6.5 cm, 96.1 ± 16.5 kg Amateur to semi-pro rugby	Whole leg (Anterior or posterior surface)	3	20 m	Acute
Rey et al. (117)	10 males, 23.6 ± 2.7 years, 178.5 ± 4.9 cm, 72.9 ± 5.2 kg Amateur soccer players	Trunk	18.9 ± 2.1	30 m	6 weeks
Macadam et al. (78)	22 males, 19.4 ± 0.5 years; 180.4 ± 7.2 cm, 97.0 ± 4.8 kg Amateur to semi-professional rugby	Forearm	2	20 m	Acute
Feser (51)	11 males, 21.2 ± 2.56 years, 175.3 ± 5.46 cm, 68.7 ± 4.30 kg Track and field amateur athletes	Thigh Shank	2	50 m	Acute
Hurst et al. (60)	6 males, 2 females, 21 ± 1 years, 172 ± 9 cm; 70.4 ± 6.4 kg University-level sprinters	Thigh Shank	1.7 0.6	40 m	Acute
Zhang et al. (157)	16 male, 21 ± 2 years, 176 ± 4 cm; 67.4 ± 5.7 kg Sub-elite sprinters	Shank	15% shank mass	40 m	Acute

WR = wearable resistance

Through advances in technology, WR has evolved from cumbersome and bulky forms of loading to technologies that are better fitting and allow a myriad of loading patterns. For example, earlier studies by Ropret et al. (119) used lead rods fixed around the ankle or that were handheld, while Cronin, et al. (31) used a weighted vest that enabled small sand bags to be inserted into pocket-type compartments (Figure 2A). Conversely, recent researchers (51, 60, 77, 78, 134-136) have used compression garment apparel that enables WR to be attached (via Velcro), to different parts of the body (Figure 2B). The compression garment-based method enables the WR to be affixed tightly to the body. Therefore, mitigates load movement and slippage, which can happen with other forms of WR (for example weighted vests) in dynamic and high velocity actions, thus potentially unduly affecting sprint performance.

Figure 2. Weighted vest with sand-bag loads (A), compression garment with Velcro attached loads (B).

2.3 Arm Wearable Resistance During Sprint-Running

Four studies (75, 82, 110, 119) have examined the effects of arm WR (Table 2). The purposes of these studies were to assess acute kinematic and kinetic changes, and longitudinal kinematic changes. The magnitude of loads ranged from 0.6% to 2% BM in acute studies, with one longitudinal study using a 2.5% BM load. The distances measured ranged between 20-50 m, and subjects ranged from physical education students to semi-professional rugby players.

In terms of the acute trends, it appears that loads ≥ 1.8% BM provide enough of an overload to significantly increase sprint times from 10 m to 30 m. Though it appears that a greater overload is needed for the start and initial acceleration phase (0 m to 10 m) to affect sprint times. With regards to kinematics, loads of ≥ 2% BM have resulted in significant increases in step length (2.1%) and contact time (6.5%), while significant decreases were found in step frequency (-4.1%) and flight time (-5.3%) (78). The only significant kinetic change was maximal horizontal power (P_{max}) (-5.5%) which significantly decreased over a 20 m sprint.

Pajić et al. (110), in the only training study, measured the effects of a six week training program with 2.5% BM arm WR over 25-50 m of sprint-running and reported there was a significant increase in stride length (3.8%), and a significant decrease in stride frequency (-3.7%). However, there was no change to maximum velocity. The adaptations to the two key determinants of speed, stride length and frequency, counteracted each other, resulting in negligible changes in velocity.

A limitation of the research to date relates to the small number of studies completed, differences between subject characteristics, and a paucity of kinematic and kinetic analyses. Though all studies measured velocity, limited kinematics were collected, with only one study reporting contact and flight times. Moreover, only one study has quantified any acute kinetic measures, which were measured from 0-20 m. As only one longitudinal study has been completed, understanding adaptations from arm WR are unclear. It needs to be noted that subjects in this longitudinal study were physical education students, with only six subjects in both the control and intervention groups. Moreover, only one stride was analysed with a high-speed frame rate camera, during the maximum velocity phase, thus limitations from sample size, rudimentary analysis and no acceleration phase analyses provides little information of high methodological quality. More research is needed to fully understand the effects of loading the arm on kinematic and kinetic determinants of speed.

Table 2. Arm wearable resistance changes to sprint performance, kinematics and kinetics (n=4).

Study	WR magnitude and placement (% body mass)	Sprint performance and velocity	Kinematics	Kinetics
Acute				
Ropret et al. (119)	0.6, 1.2, 1.8 Hand-held	AP: Maximum Velocity 0.9% (1.8% BM) MVP: Maximum Velocity -1%* (1.8% BM)	AP: SF 0%, SL -1.3% (1.2% BM) MVP: SF -1.2% (0.6% BM) SL 1.1%, -0.6%, -1.1%	
McNaughton & Kelly (82)	1 kg Forearm	10 m time -1% 40 m time 0.2% Maximum Velocity -0.6%		
Macadam et al. (78)	2 Forearm	2m 2.7%, 5 m 2.4% 10 m 2.1%*, 20 m 2.0%* 10-20 m 2.0%* V_0 -1.4%*	AP: SPL 2.1%*, SPF -4.1%*, FT -5.3%*, CT 6.5%*	Rel F_0 -4.2% Rel P_{max} -5.5%* Rel Fv profile -3.0%
Longitudinal				
Pajić et al. (110)	2.5 Arms	Maximum Velocity 0%	MVP: SL 3.8*, SF -3.7**	

CT = contact time; SF = stride frequency; SPF = step frequency; SL = step length; SP = start phase; AP = acceleration phase; MVP = maximal velocity phase; P_{max} = maximal horizontal power; V_0 = theoretical maximal velocity; F_0 = theoretical maximal horizontal force; Rel = relative to system mass; WR = wearable resistance
* = $p < 0.05$; ** = $p < 0.01$

Although the importance of arm action during sprint-running has received little attention in the literature, a recent review highlighted that the arms may play an important role in sprint performance, particularly during the start and acceleration phase (75). Given the available information regarding arm WR, it would seem that for the sprint start and early acceleration phases at the very least, that when WR is attached to the arms, this form of loading appears to increase step and stride length which mitigates the overload to step and stride frequency resulting in comparable sprint times up to 10 m. It could be assumed that the acute and longitudinal increases in step and stride length from arm loading were due to similar ground reaction force magnitudes applied over a longer contact time, that is greater horizontal impulse. However, whether such assumptions are accurate would need force plates to quantify the vertical and horizontal ground reaction forces used in tandem with motion capture to capture changes in joint angle positions. Though arm WR also decreased step and stride frequency, thus moderating any potential increases in velocity, further longitudinal studies are required to assess the potential benefits to sprint-running performance. Given that step frequency is overloaded, this may provide a training method to enhance arm-leg frequency, especially during maximum velocity. Moreover, during treadmill running, arm swing was found to increase the vertical displacement of the body's centre of mass (5-10%) through the upward acceleration of the arms, relative to the trunk (57). Therefore, given the upright position of treadmill running, future research into the role of the arms with WR during the maximum velocity phase is required. From the small body of literature examining arm WR, this form of loading may provide a sprint specific overload of the arm action during sprint-running that could serve as a suitable method for cueing and improving arm drive mechanics. Figure 3 depicts this form of loading during a crouched start position, the arm loading potentially a suitable method for cueing and improving arm drive mechanics, and therefore developing a great propulsive emphasis during early acceleration.

Figure 3. Wearable resistance attached to the forearms during crouched sprint start take-off.

2.4 Trunk Wearable Resistance During Sprint-Running

Nine trunk positioned WR studies (9, 26, 31, 36, 65, 115, 117, 130, 134) are summarised in Table 3. Four acute studies used loads ranging 5-21.8% BM, while five longitudinal studies used loads ranging 5.6-18.9% BM. Over ground distances measured ranged from 10-50 m, while non-motorised treadmill sprint-running was measured over a duration of 6 seconds, and subjects ranged from sedentary to national level rugby players.

Acute over ground sprint times were increased (that is sprints were slower) with ≥ 5% BM over distances between 10 m and 50 m, with greater changes found during the maximum velocity phase as compared to the the acceleration phase. No measures of velocity during over ground sprint-running were reported, though velocity was measured during non-motorised treadmill sprints, which only significantly decreased with WR loads of ≥ 10.9% BM. With regards to step kinematics, 5% BM significantly increased contact time (4.7%) but only during the maximum velocity phase of treadmill sprinting, though no other kinematic changes occurred with this magnitude of loading. During over ground sprinting, contact times (12.8-24.5%) and flight times (-12.8% to -24.5%) were found to be more sensistive than stride variables (~ 2.6-6.1%) with loads of ≥ 15% BM, with comparable findings in treadmill sprints. For kinetics, only measurements from non-motorised treadmill studies have been reported. When a relatively heavy load (> 20% BM) was used, trunk WR significantly increased (~8%) vertical GRF during the maximum velocity phase, most likely due to the smaller rise in centre of gravity. While with 5% BM, vertical GRF was significantly decreased (~-6%), during the maximum velocity phase. No other significant changes to kinetics were found with any loading.

Mixed results were found in longitudinal studies which may be due to methodological differences between studies. Significant and non-significant improvements in velocity (1.2-1.3%) and sprint times (10 m = 9.4%, 30-50 m = 1.2-6.1%) were found in four longitudinal studies (3-7 weeks), while an 8-day study found no change in sprint times. No kinetic measures were reported from any study, while only two studies assessed kinematics.

Several limitations exist from the current research investigating trunk WR. Firstly, no kinetic measures during either acute or longitudinal over ground studies have been collected limiting the understanding of kinetic determinants of speed with trunk WR. Secondly, loads of <15% BM have not measured step kinematics during over ground sprint-running, while loads between 11% and 22% BM, and over have yet to be investigated in non-motorised treadmill sprints. In terms of longitudinal studies, the differences in methodologies: subjects (sedentary to national level), training durations (8 days to 7 weeks), sprint distances (10-55 m) and magnitudes of WR (~5-19% BM), mean that a clear understanding of adaptation is uncertain.

Table 3. Trunk wearable resistance changes to sprint performance, kinematics and kinetics (n=9).

Study	WR magnitude (% body mass)	Sprint performance and velocity	Kinematics	Kinetics
Acute				
Simperingham & Cronin (134)	5	2 m -0.9%, 5 m -0.6% 10 m -0.8%, 15 m -0.3% 20 m 0.0%, 25 m 0.4% Peak velocity 0.4% AP, 1.2% MVP	CT 3.8% AP, 4.7 % MVP* FT -15% AP* -7.9% MVP SPL 0.0% AP, 2.5% MVP SPF -0.7% AP, -3.8% MVP	F_v -1.7% AP, -0.6 % MVP Rel F_v −5.4% AP, −6.4%, MVP* Rel F_v mean −3.8% AP, −4.0% MVP* P_{max} -1.4% AP, -4.3% MVP F_h -1.0% AP, -2.7% MVP
Konstantinos et al. (65)	5 10 15	10 m 4.1%*, 20 m 4.7%*, 30 m 4.6%*, 40 m 5.1%*, 50 m 4.6%* 10 m 6.9%*, 20 m 7.4%*, 30 m 6.9%*, 40 m 7.5%*, 50 m 7.3%* 10 m 9.9%*, 20 m 9.3%*, 30 m 9.2%*, 40 m 9.9%*, 50 m 8.2%*		
Cross et al.	10.9	Peak velocity -3.6%*	CT -4.1% AP, 5.6%	F_v -4.1% AP, 3.1%

(36)	21.8	Peak velocity -5.7%*	MVP* FT -20% AP, -17.4% MVP* SPL -4.4% MVP* SPF 0.8% MVP CT 1.4% AP, 9.2% MVP* FT -26.7%* AP, -18.9%* MVP SPL -4.4% MVP* SPF -1.5% MVP	MVP F_v mean 3.4% AP and MVP P_{max} 0% AP, -3.7% MVP F_h -6.1% AP, 0.8% MVP F_v 3.7% AP, 8.2%* MVP F_v mean 10.6%* AP, 11.1%* MVP P_{max} 7.9% AP, -14.3%* MVP F_h -6.2% AP, -6.3% MVP
Cronin et al. (31)	15 20	10 m (% unknown) 30 m (% unknown) 10 m 9.3% * 30 m 11.7% *	CT 12.8%* FT – 8.4%* CT 24.5%* FT – 14.4%*	
Longitudinal				
Rantalainen et al. (115)	5.6	Velocity 1.3%		
Scudamore et al. (130)	11.6	36.6 m -1.5% **		
Barr et al. (9)	12	10 m 0.0% 30 m 0.0% 40 m 0.0%	CT 0.0% AP, 8.9%* MVP FT 0.0% AP, 8.4% MVP SL 0.8% AP, 2.5% MVP	
Clark et al. (26)	18.5	55 m −1.2% Maximum Velocity 1.2%	SPL -2.2% SPF 3.4% CT -1.5% FT - 5.4%	
Rey et al. (117)	18.9	10 m -9.4% ** 30 m -6.1%**		

CT = contact time; SF = stride frequency; SPF = step frequency; SL = stride length; SPL = step length; SP = start phase; AP = acceleration phase; MVP = maximal velocity phase; F_h = horizontal ground reaction force; F_v = vertical ground reaction force; P_{max} = maximal horizontal power; Rel = relative to system mass; WR = wearable resistance;
* = $p < 0.05$; ** = $p < 0.01$

Sprint-running with trunk WR enables the WR to be evenly distributed near an individual's centre of mass potentially increasing the ability to produce greater ground reaction forces and power production to overcome this form of overload. While trunk positioned WR seem to have less effect in the acceleration phase than maximum velocity phase, they do offer the advantage of no direct overload to the limbs resulting in less changes in step length and step frequency. Trunk WR may be a suitable form of WR for the maximum velocity phase due to the greater magnitude of WR that can be attached to the larger suface area (Figure 4). Subsequently, WR may be appropriate to overload vertical stiffness, and specifically target reactive strength development for maximum velocity sprinting possibly due to the greater magnitude from the vertical load imposed. Moreover, though vertical GRF did not acutely increase, mostly likely due to a decrease in centre of gravity height change, vertical impulse may be increased due to the greater overall vertical load imposed and increases in contact time. Due to vertical loading, this WR placement appears to affect acceleration less as compared to the maximum velocity phase as propulsion is directed more horizontally while accelerating with WR.

Due to a lack of comparable methodologies and a dearth of research into the kinematics and kinetics during training studies, the underlying mechanisms for sprint improvements remains unknown. Future studies should consider the type of trunk WR apparel, which is used, with loose fitting weighted vests considered less efficient for sprinting due to the unwanted movement around the trunk, in comparison to compression garment apparel which enables a skin-tight fitting (Figure 2).

Figure 4. Example of trunk loaded wearable resistance.

2.5 Leg Wearable Resistance During Sprint-Running

Nine leg WR studies (13, 51, 60, 77, 110, 119, 134, 136, 157) have been completed to date (Table 4). The magnitude of loads ranged from 0.6% to 5% BM in acute studies, with one longitudinal study using 2.5% BM. Sprint distances measured ranged from 2-50 m, while non-motorised treadmill sprinting was measured over durations up to 6 seconds, and subjects ranged from physical education students to professional beach sprinters.

In terms of the acute sprint times, it appears that whole leg loads ≥ 5% BM are required to provide enough of an overload to significantly increase sprint times, but only for sprint distances of ≥ 15 m during treadmill sprints and ≥ 20 m during over ground sprints. However, whole leg loads of ≤ 3% BM, thigh or shank loads of ≤ 2% BM, and ankle loads ≤ 1.6 % BM, all significantly decreased velocity. Moreover, greater decreases in velocity were found during the maximum velocity phase compared to the acceleration phase.

In terms of kinematics, all WR placements (loads < 5% BM) significantly decreased (-2.9% to -11.9%) step and stride frequency. However, step and stride length were minimally changed, with no significant differences found with any WR loads and positions (-1.7% to 6.0%). When the WR was attached in a more distal position (shank or ankle), greater kinematic changes were found compared to the studies which used thigh, or whole leg loading. Zhang et al. (157) assessed joint kinematics and found that shank WR significantly decreased (-5.1%) knee joint angle at landing, however, this was the only study to report joint kinematics. From acute over ground kinetic findings with whole leg WR of 3% and 5% BM, WR resulted in a more force-oriented force-velocity (*F–v*) curve, but only 3% BM produced a significant increase (~10%) from the unloaded condition, with 5% BM producing a non-significant 6.1% increase. During treadmill sprints, the 5% BM whole leg condition significantly increased vertical GRF (~4%) but did not significatly overload any other kinetic measures.

From the only longitudinal study (six week training utilising 2.5% BM ankle WR) that measured kinematic changes between 25-50 m, Pajić et al. (110) reported a significant increase in stride length (5.3%) and decrease in stride frequency (-5.6%), though no significant changes to maximal velocity. It appears that, similar to findings with the arm loading by the same authors, adaptations to the determinants of speed counteracted each other, resulting in negligible changes in velocity. Moreover, as previously mentioned in the arm section, this paper has several methodological limitations, thus is lacking in high methodological quality.

A limitation of the current body of research relates to no quantified kinetic measures beyond 20 m, therefore, how leg WR affects kinetics in the maximum velocity phase is unknown. Moreover, though several acute studies have measured a range of loads and placements, only one longitudinal study has been completed with leg WR. Therefore, further research is required to ascertain how this form of loading may affect sprint performance adaptation.

Table 4. Leg wearable resistance changes to sprint performance, kinematics and kinetics (n=9).

Study	WR magnitude and placement (% body mass)	Sprint performance and velocity	Kinematics	Kinetics
Acute				
Ropret et al. (119)	1.6, 3.2, 4.8 Ankle	AP: Velocity -3.6%**, -4.6% **, -7.8%** MVP: Velocity -4.2%**, -8.5% **, -12.8%**	AP: SF -2.9%**, -6.7%**, -8.7%** SL -0.8%, -1.7%, -1.4% MVP: SF -5.9%**, -9.55**, -11.9%** SL 0.5%, 1.9%, 1.9%	
Bennett et al. (13)	2.4 Whole leg	0-10 m -0.6%, 10-20 m 4.2%**	MVP: Stride velocity -4.7%**	

		20-30 m 3.7%, 30-40 m 7.4%** 40 m 3.1%	CT 8.9%, FT 0.8% , SF -2.2%,	
Simperingham & Cronin (134)	5 Whole leg	2 m-1.8%, 5 m 0.0% 10 m 1.1%, 15 m 2.1%* 20 m 2.5%*, 25 m 3.3%* Peak velocity -2.3%* AP, -5.3%* MVP	CT 4.3%* AP, 4.7%* MVP FT 0.0% AP, 0.0% MVP SPF -3.7%* AP, -3.5%* MVP SPL 6.0% AP, -1.7% MVP	F_v 4.0%* AP, 4.5%* MVP F_v mean 4.1%* AP, 4.0% MVP F_h 0.6% AP, 1.9% MVP - P_{max} -0.8% AP, -3.1% MVP Rel F_v -0.9% AP, -0.8% MVP
Simperingham et al. (136)	3 Whole leg 5 Whole leg	5 m -1.5% 10 m-0.5% 20 m 0.6% V_0 -3.6%* 5 m 0.7% 10 m 0.9% 20 m 2.0%* V_0 -6%*	CT 5.0%* SP, 5.0%* AP FT-19.4% SP, -3.8% AP SPF -1.5% SP, -2.0%* AP SPL 0.8% SP, 0.0% AP CT 5.0%* SP, 6.0%* AP FT -17.7% SP, -3.8% AP SPF -2.0% SP, -3.0%* AP SPL 0.0% SP, -0.6% AP	Rel F_0 6.25% Rel P_{max} 1.2% Rel S_{Fv} 10.0%* Rel F_0 3% Rel P_{max} -4.2% Rel S_{Fv} . 6.1%
Macadam et al. (77)	3 Whole leg, anterior 3 Whole leg, posterior	2 m -1.2%, 5 m 0.0% 10 m 0.0%, 20 m 0.8% 10-20m 2.2%* V_0 -5.4%* 2 m -1.2%, 5m 0.0% 10 m 0.5%, 20 m 1.4% 10-20 m 2.9%* V_0 -6.5%*	CT 3.4%* SP, 3.0%* AP FT -7.3% SP, 1.3% AP SPF-1.3% SP, -3.4%* AP SPL 0.0% AP and SP VS -6.4%* AP, -5.8% SP CT 4.4%* SP, 3.0%* AP FT -7.3% SP, 2.5% AP SPF -1.3% SP, -3.6%* AP SPL 0.8% SP, 0.0% AP VS -8.3%* SP, -6.2%* AP	F_0 5.4%, Rel F_0 5.5% S_{Fv} 12.2%*, Rel S_{Fv} -9.9% * P_{max} 1.5%, Rel P_{max} 0.0% F_0 4.7%, Rel F_0 5.1% S_{Fv} 11.7%*, Rel S_{Fv} -9.9%* P_{max} 0.6%, Rel P_{max} -1.3%
Feser et al. (51)	2 Thigh 2 Shank	10 m 0.5% 50 m 0.3% Maximum Velocity -1.8% * 10 m -0.5% 50 m -0.1% Maximum Velocity -2% *	CT 2.6% AP, 2.9%* MVP FT 0% AP and MVP SPL 0% AP, -0.5% MVP SPF -1.4% AP, -1.4%* MVP SPW 0% AP, 10% MVP CT 1.9% AP, 2.1%* MVP FT 2% AP, 3.3%* MVP SPL 0% AP, -0.5% MVP SPF -2.1%* AP, -2.5%% MVP SPW 0% AP and MVP	
Hurst et al. (60)	1.7 Thigh 0.6 Shank	Maximum Velocity -1.8% †† Maximum Velocity -1.4% ††	CT 2.5% MVP †††, FT 4.5% MVP SPL 1.5% MVP, SPF -3.7% MVP ††† CT 1.2% MVP ††, FT 2.8% MVP †† SPL 1% MVP †, SPF -2.3% MVP †††	
Zhang et al. (157)	15% of shank mass	Maximum Velocity -2.3% **	Hip joint angle at landing 1.9% Knee joint angle at landing – 5.1% * Ankle joint angle at landing 5.3% Hip joint angle at take-off -14.2% Knee joint angle at take-off – 1.9% Ankle joint angle at take-off -12.7%	

Longitudinal				
Pajić et al.(110)	2.5 Ankle	MVP: Maximum Velocity 0.5%	MVP: SL 5.3% **, SF -5.6%**	

CT = contact time; SF = stride frequency; SPF = step frequency; SL = step length; VS = vertical stiffness; SP = start phase; AP = acceleration phase; MVP = maximal velocity phase; F_v = vertical ground reaction force; F_h = horizontal ground reaction force; P_{max} = maximal horizontal power; Rel = relative to system mass; V_0 = theoretical maximal velocity; F_0 = theoretical maximal horizontal force; S_{Fv} = slope of the force-velocity curve; WR = wearable resistance; * = $p < 0.05$; ** = $p < 0.01$, † = possible trivial difference; †† = possible clear difference; ††† = likely clear difference

Due to the significant changes in step frequency, leg WR may enable a specific method to overload and improve leg drive mechanics. This form of WR during sprint-running can be used to provide a rotational overload to the hip and knee joints. However, attaching a load directly to the limb will change the inertia properties of the limb, potentially resulting in changes to movement mechanics (81). Therefore, it is important to understand how leg WR placement may change sprint running movement mechanics prior to further investigating its use as a training tool. Practitioners may be interested in understanding the effect of placing the WR more distal to the hip joint, for example shank (Figure 5) vs. thigh (Figure 6) which introduces an additional inertial manipulation to the knee joint. Furthermore, there has been no clarification in the research as to the placement of load on the respective limbs, such as proximal thigh vs. distal thigh, which likely provides a different overload. Figure 7 shows the same magnitude of WR positioned on different areas of the thigh segment, which results in differences in inertial manipulation. More research about load placement is needed.

Figure 5. Example wearable resistance loading for shank.

Figure 6. Example wearable resistance loading for thigh.

Figure 7. Wearable resistance placed mid femur and distal femur from hip joint.

Lower body WR may provide a non-verbal training cue for improved sprint-running mechanics. The additional load positioned on the legs lowers the subject's centre of gravity and may reinforce the ideal piston like mechanical action of the legs (providing strong negative feedback for letting the lower shank swing through), and perhaps encouraging a more horizontal ground reaction force application. Future research is needed to investigate such a contention. To summarise, it seems that leg WR of as little as of 2% BM and as much as 5% BM can be used to overload contact time and step frequency during sprint-running. It is possible that leg WR results in the athletes responding by increasing their force production, which mitigates decreases in step frequency, contributing to the similar sprint times to unloaded sprinting up to 10 m. This was certainly the case in two studies that used WR of 3% BM, suggesting that this magnitude of WR may provide a stimulus to increase horizontal force output. Therefore, it may be concluded that leg WR has the potential to elicit improved sprinting performance over time through greater horizontal force production.

2.6 Acute Enhancement During Sprint-Running from Wearable Resistance

Three studies (13, 134, 135) have assessed the effects of WR on acute enhancement of sprint times with loads of 1-5% BM attached to the leg or trunk (Table 5). During a single-subject study design it was found that the start and acceleration phase kinematics were substantially changed (greater than two standard deviations [SD] from baseline) following a series of 40 m sprints with incremental WR (1%, 3%, 5% BM) (135). Contact time was substantially increased by 2.9% (start phase) and 2.1% (acceleration phase) with a substantial decrease in 10 m sprint time by 3.3%, while during the maximal velocity phase, substantial changes to both flight time (3.2%) and step frequency (-2.5%) were reported with only a slight increase to the 30-40 m split time (1.8%) (135). No change in time to 40 m was reported by Simperingham, et al. (135), while Bennett, et al. (13) reported no significant changes (0.3%) to 40 m sprint times following a 2.4% BM WR protocol. With a greater magnitude of WR (5% BM) protocol, no significant changes to performance were found aside from a 1.3% increase in vertical GRF production during non-motorised treadmill sprinting with leg WR (134).

Further studies with greater loads (≥ 5% BM) are required to explore possible acute enhancement effects from WR. Moreover, the effects of WR loading of the arms have yet to be investigated in over ground sprint-running, which may result in different kinematic and kinetic changes, given the prior discussed changes from different WR positions in the earlier sections of this review. Future studies wishing to use a greater magnitude of WR may wish to load multiple areas of the body together (trunk and legs), though further investigation is required to ascertain the optimum WR position and magnitude.

Table 5. Acute enhancement effects from wearable resistance on sprint-running performance (n=3).

Study	WR magnitude and position (% body mass)	Training protocol	Sprint performance and velocity	Kinematics	Kinetics
Bennett et al. (13)	2.4 Whole leg	7 repetitions of 40 m sprints: 2 x unloaded (pre-test), 2 x WR, 3 x unloaded (post-test) Rest time unknown	0-10 m 0.0% 10-20 m 2.6% 20-30 m 1.8% 30-40 m 1.8% 40 m 0.3%	MVP: stride velocity -0.8% CT 2.2% FT -0.8% SF 0.4%	
Simperingham & Cronin (134)	5 Whole leg 5 Trunk	4 sets of 2 max effort 6 s sprints on a non-motorised treadmill: Sets 1 and 4 unloaded, sets 2 and 3 trunk or leg loading randomised. 3-5 mins of rest			MVP F_v 1.3%*
Simperingham et al. (135)	1, 3, 5 Whole leg	3 x 40 m sprints: 1 x 1% BM, 1 x 3% BM, 1x 5% BM. 5 mins of rest	10 m -3.3%^ 30 m-0.7% 40 m 0.0% 30-40 m 1.8%	CT 2.9%^ SP, 2.1%^ AP, 1.9% MVP FT -1.8% SP, 1.2% AP, 3.2%^ MVP SPF -1.4% SP, -1.8%^ AP, -2.5%^ MVP SPL 1.8% SP, 1.3% AP, 0.5% MVP VS -5.0% SP, -6.1% AP, 1.5% MVP	

CT = contact time; SF = stride frequency; SPF = step frequency; SL = step length; SP = start phase; AP = acceleration phase; MVP = maximal velocity phase; F_v = vertical ground reaction force; WR = wearable resistance
* = p < 0.05 with whole leg WR; ^ = more than 2 standard deviations from baseline mean

2.7 Limitations and Future Research

A limitation of the studies to date relates to the small number of longitudinal studies, differences between subject characteristics, and a lack of kinematic and kinetic analyses in different phases of a sprint. From the majority of the research, the subjects tested have been males with the exception of one study that contained male and female subjects, therefore, future research is required to ascertain how WR affects female sprint-running performance. Further research is required to test the acute and longitudinal efficacy of this training method with a different group of athletes. Quantifying the changes in sprint kinetics, as well as sprint kinematics, and considering the impact of subject strength and sprint level will also enhance the understanding of this topic. Moreover, there is currently an inability in the literature to explain rotational workload when WR is attached to the limbs, therefore future research should explore this area.

2.8 Conclusions

The principle of specificity provides insights into how loading and training stimuli can be applied to optimise transference to the activity or sport of interest. In this regard, it is desirable that the contraction forces, movement velocities, and technical demands simulate the activity of interest. WR may provide such a stimulus in terms a sprint specific overload, with different magnitudes and placement positions enabling the practitioner to target different mechanical determinants of sprint-running.

The start and acceleration phase of sprint-running are typified by a longer stance phase resulting in greater propulsion and horizontal force production compared with the maximum velocity phase. During the start and early sprint acceleration, the orientation of forces has been found to be a greater indicator of sprint performance than the overall magnitude (87). Therefore, athletes that train with differing body orientations, and thus force application techniques, may exhibit different acceleration capabilities (35). A summary of WR changes during the acceleration phase can be found in Table 6. Irrespective of the WR position, start and early acceleration is less affected by WR with no significant changes in acute sprint times up to 10 m. However, beyond this distance sprint times have been found to be significantly increased (that is slower) compared to unloaded sprint-running when loads ≥ 2% BM are used for arm loading, or ≥ 5% BM for leg and trunk loading. Though small magnitudes of WR (~2% BM) provide a sufficient overload to kinematic and kinetic variables during limb loading, it would seem greater magnitudes are required (> 10% BM) during trunk loading.

Table 6. Summary of acute and longitudinal changes to kinematic and kinetic variables with different wearable resistance placement and magnitudes during the acceleration phase of sprint-running.

% body mass	Sprint times (<20 m)	SL	SF	CT	FT	V_0	F_0	P_{max}	F-v	vGRF	hGRF
Arm											
≤1%		=	=			=					
>1-2%		=	=			=					
≥2%	↑ ≥10m	↑	↓	↑	↓	↓	=	↓	=		
Trunk											
≤5%	= treadmill, ↑ overground	=	=	=	↓	=		=		=	=
>5-10%	↑					==					
≥10-15%	↑			↑	↓	↓	↓	=		=	=
	==	==	==	==	==						
≥15-20%	↑			↑	↓						
	⇣	==									
≥20%				↑	↓	↓	↓	=		↑ mean	=
Leg											
>1-2%	=	=	↓	↑	=	↓					
≥2-3%	=	=	=	↑	=	↓					
		⇡	⇣			==					
≥3-4%	=	=	↓	↑	=	↓	=	=	↑		
≥4%	↓ ≥15m	=	↓	↑	=	↓	=	=	=	↑	=

↑ : acute study, ⇡ : longitudinal study, = : no significant acute change, == : no significant longitudinal change

SL : step and stride length; SF : step and stride frequency; CT : contact time; FT : flight time; V_0 : maximum velocity; F_0 : maximum horizontal force; P_{max} : maximum horizontal power; F-v : force-velocity slope; Rel : relative to system mass; hGRF : horizontal ground reaction force; vGRF : vertical ground reaction force

During the maximum velocity phase, kinematic differences in body position (more upright trunk) and kinetic difference (horizontal force decreases, vertical force nominal changes) exist compared to earlier phases of sprint-running. A summary of WR changes during the maximum velocity phase can be found in Table 7. Though differences between individuals and cohorts mean maximum velocity is achieived at different distances, a consensus exists that for sub elite athletes and team sport athletes, maximum velocity may be attained during 20-30 m of a sprint. As the majority of subjects in the studies reviewed fall within this grouping, and several studies identified maximum velocity within the 20-30 m range, acute sprint times ≥ 20 m were significantly increased with all WR positions when magnitudes of > 2% BM were used. Leg loading of < 1% BM was sufficient to overload kinematics during this phase, while loading of ≥ 2% BM was required with arm WR, and ≥ 5% BM with trunk WR. From the small body of longitudinal studies, no change to sprint times has been found with limb WR. Longitudinal use of trunk WR was found to improve sprint times during the maximum velocity phase of some studies, whereas other researchers reported no change.

Table 7. Summary of acute and longitudinal changes to kinematic and kinetic variables with different wearable resistance placement and magnitudes during the maximum velocity phase of sprint-running.

% body mass	Sprint times (≥ 20 m)	SL	SF	CT	FT	V_0	F_0	P_{max}	F-v	vGRF	hGRF
Arm											
≤1%		=	=			=					
>1-2%		=	=			↓					
≥2%	↑					↓	=	↓	=		
		⇡	⇣			==					
Trunk											
≤5%	= treadmill, ↑ overground	=	=	↑	=	=		=		= rel	=
>5-10%	↑										
≥10-15%	↑	↓	=	↑	↓	↓		=		=	=
	==	==		⇡	==						
≥15-20%	↑										
	⇣ 30 m == > 30 m	==	==	==	==	==					
≥20%		↓	↓			↓		↓		↑ mean	=
Leg											
≤1%		↑	↓	↑	↑	↓					
>1-2%		=	↓	↑	=	↓					
≥2-3%	↑ whole leg = thigh = shank	=	↓ thigh = whole leg = shank	↑ thigh ↑ shank = whole leg	↑ shank = whole leg = thigh	↓					
		⇡	⇣								
≥3-4%							=	=	↑		

≥4%	↑	=	↓	↑	=	↓		=		↑	=

↑ : acute study, ⇡ : longitudinal study, = : no significant acute change, == : no significant longitudinal change

SL : step and stride length; SF : step and stride frequency; CT : contact time, FT : flight time, V_0 : maximum velocity; Fo : maximum horizontal force; P_{max} : maximum horizontal power; F-v : force-velocity slope; Rel : relative to system mass; hGRF : horizontal ground reaction force; vGRF : vertical ground reaction force

WR attached to the arms during the sprint action may be a suitable method for cueing and improving arm drive mechanics. The increase in step length found during the initial take-off requires further acute research to verify this finding and long-term research to determine adaptations. Trunk positioned WR offers the greater magnitude of WR to be attached to the athlete resulting in a greater vertical GRF to be overcome. Moreover, this placement seemingly alters step variables to a lesser extent compared to other WR placements with comparable loads, as the limbs are not directly loaded. As the orientation of force demands shift from horizontal during the acceleration phase to vertical during the maximum velocity phase, greater vertical GRF with trunk WR seemingly overloads the maximum velocity phase of the sprint more than the acceleration phase. Leg WR overloads the frequency of the leg action while seemingly having minimal impact on step length. Furthermore, WR at the shank or ankle would also place a greater eccentric demand on the hamstrings during mid to late swing phase, providing a high-velocity training stimulus to potentially strengthen the hamstrings. WR attached to the legs provides an overload during the stance phase resulting in the athlete having to produce a greater amount of force to overcome the additional loading. For athletes requiring a more force dominant *F–v* profile, and for relatively velocity dominant athletes, sprint running with leg WR may enable the athlete to improve their external horizontal force production.

Though different WR positions seemingly offer differential overload and potential training benefits, longitudinal sprint studies are required to verify the findings of this review. It is suggested that sprint-running with WR can be used as an adjunct training tool to other forms of resistance training programs by promoting intermuscular co-ordination through the strategic placement of light variable resistance.

Chapter 3. Quantification of the Validity and Reliability of Sprint Performance Metrics Computed using Inertial Sensors: A Systematic Review

This chapter comprises the following paper published in Gait and Posture Journal.

Reference: Macadam, P., Cronin, J., Diewald, S., Neville, J. (2019). Quantification of the validity and reliability of sprint performance metrics computed using inertial sensors: a systematic review. *Gait & Posture*, 73, 26-38. doi: 10.1016/j.gaitpost.2019.07.123

Author contributions: Macadam 85%, Cronin 10%, Diewald, 2.5% Neville 2.5%

3.0 Prelude

The popularity of sprint-running in both recreational settings and in sport training and competitive games has encouraged a considerable body of research and assessment. This has been potentiated by advances in technology. Accurately capturing and analysing kinematic data (steps, joint angles, velocities, and accelerations) and kinetic data (forces and power output) is of great importance to practitioners, as the information can provide a great deal of insight into movement performance and irregularities. Measurements of kinematics and kinetics during sprint-running have been investigated using high-speed frame cameras, timing gates, force plates and motion analysis systems. However, these systems require dedicated space, expensive equipment, can require lengthy test setup and data processing times, have limited capture volume and thus may reduce specificity to the desired activity. Furthermore, for some equipment measurements, subjects are restricted to a confined area in a laboratory, and therefore, the system can only capture a small amount of continuous data. One measurement tool not restricted to these limitations are wearable inertial sensors. These sensors have been used to analyse kinematic movement parameters such as jumping, walking and running and sprinting in both laboratory and field-based settings. Given the more practical applications of the sensors, measurements from these sensors may be of more use to practitioners. The purpose of this chapter was to review the validity and reliability of inertial sensors to referenced systems during sprint-running. The reported findings will be used for investigating the application of IMUs during sprint-running in subsequent studies.

3.1 Introduction

Many sports, including athletics and team sports, require athletes to perform maximal effort sprinting. Sprinting is a complex form of motion utilising all the major structures in the human body. The popularity of this activity and its importance in sport has encouraged a considerable body of research in this area. This understanding has been enhanced by advances in technology including wearable sensors, faster frame rate cameras, force plates, and improved motion analysis systems. Accurately capturing and analysing kinematic data (steps, joint angles, velocities, and accelerations) and kinetic data (forces and power output) is of great importance to practitioners, as the information is able to provide insights into movement performance and irregularities (22, 105). Ideally an athlete's sprint performance should be measured within their natural sporting context ensuring that any findings are ecologically valid and meaningful. This is highlighted in research that has found differences in kinematics and kinetics between non-motorised, and motorised, treadmill running and sprinting, compared to over ground running and sprinting (24, 118, 126).

During sprinting, leg muscles support the body against gravity and accelerate or decelerate the body in a forward direction (61). External forces act on the body, including ground reaction forces (GRF) and inertial forces from moving body segments, which need to be balanced by internal forces developed from muscles, tendons, ligaments and joint capsules (107). Measurement of these external forces and temporal parameters can be acquired through laboratory equipment such as force plate technology and optical motion analysis systems, but only within definable and limited spatial boundaries (129). Force platforms allow measurement of the three orthogonal components of the GRF vector during a single running step. Optical motion analysis systems use sets of cameras, passive or active markers, and software to calculate joint kinematics and spatio-temporal parameters and are considered the gold standard reference for human motion analysis (69). However, these systems require dedicated space, expensive equipment, and can require lengthy test setup and data processing times. Furthermore, subjects are restricted to a confined area in the laboratory, and therefore, the system can only capture a small amount of continuous data (144). Although high-speed cameras, timing gates and laser or radar guns can be used to provide a field-based testing environment, they lack some of the kinematic and kinetic measurement parameters found with the use of other devices. Moreover, they have limited capture volume and thus may reduce specificity to the desired activity. Field-based testing, however, can be used to characterise the general mechanical ability to produce horizontal external force of the subject during sprint-running, as reflected in the linear force–velocity (F–v) relationship obtained from direct mechanical-based procedures that use the centre of mass displacement estimate (34, 123). Subsequently, the mechanical capabilities of the lower limbs can be characterised by the variables: V_o, F_o, P_{max}, S_{fv}, and rate of decrease in ratio of forces (D_{rf}) (114). However, these mechanical-based procedures calculate horizontal forces from time and distance derived variables and are also likely not to detect inter-step variability as the models give the average tendency of change in GRF components with time of both limbs (132).

One measurement tool not restricted to the aforementioned boundaries are wearable inertial sensors, such as an accelerometer or inertial measurement unit (IMU), which not only contains an accelerometer, but also a gyroscope, and often a magnetometer. These sensors have been used to analyse kinematic movement parameters such as jumping, walking and running in both laboratory and field based settings (10, 29). Advances in microelectromechanical systems have enabled these portable, low cost, and low power body mounted sensors to be attached to various areas of the body enabling motion analysis for biomechanical research (69). Accelerometers measure human movement in terms of acceleration in up to three orthogonal planes: vertical, anterio-posterior, and medio-lateral (3). Modern IMU’s collect data from tri-axial accelerometers (linear acceleration measurements) and tri-axial gyroscopes (angular velocity measurements) without external references (49), thus providing a more practical approach to data collection.

Measurements of kinematics and kinetics during sprinting have been investigated using high-speed cameras, timing gates, force plates and motion analysis systems, however, given the more practical applications of the aforementioned sensors; measurements from these inertial sensors may be of more use to practitioners. Norris, et al. (105), in a review of wearable sensors during running, suggested that placement of sensors closest to the area of interest along with the use of bi/tri-axial accelerometers appeared to provide the most accurate results. However, notwithstanding this suggestion, the efficacy of inertial sensors for quantifying sprint performance is poorly understood. Therefore, the purpose of this article was to review the validity and reliability of inertial sensors to referenced systems during sprinting.

3.2 Methods

3.2.1 Literature Search Strategy

The review was conducted in accordance with the preferred reporting items for systematic reviews and meta-analyses (PRISMA) statement guidelines (86). A systematic search of the literature was undertaken for studies that used wearable IMUs and accelerometers during sprinting that assessed validity and reliability. Articles were found from international peer-reviewed journals or conference papers from inception to October 2018. The following Boolean phrases were used for the searches ((run* OR sprinting OR sprint*) AND (IMU OR inertial sensor OR wearable sensor OR accelerometer OR gyroscope) AND (valid* OR reliabil*)). Additional studies were also found by reviewing the reference lists from the retrieved studies.

3.2.2 Inclusion and Exclusion Criteria

Studies with injury-free subjects of any age, gender or activity level were included. No restrictions were imposed on publication date or publication status. Studies were limited to the English language and only full-text articles were included from peer reviewed journals or conference papers. Studies were included that involved maximum effort sprinting, therefore, sub max sprints or running studies were excluded. Moreover, studies were excluded that did not present the numerical result (i.e. results presented as figures/graphs).

3.2.3 Study Selection

One reviewer searched the databases and selected studies. The other reviewers were available to assist with study eligibility. A search of electronic databases and a scan of article reference lists revealed 374 relevant studies, with an additional 11 studies found via hand searches of the article's reference list. Details from each database were:

Pubmed: Search = ((run* OR sprinting OR sprint*) AND (IMU OR inertial sensor OR wearable sensor OR accelerometer OR gyroscope) AND (valid* OR reliabil*))
9 retrieved

SPORTDiscus (1988-2018): Search = ((run* OR sprinting OR sprint*) AND (IMU OR inertial sensor OR wearable sensor OR accelerometer OR gyroscope) AND (valid* OR reliabil*))
Source types = academic journals
143 retrieved

Web of science (1980-2018): Search = ((run* OR sprinting OR sprint*) AND (IMU OR inertial sensor OR wearable sensor OR accelerometer OR gyroscope) AND (valid* OR reliabil*))
Categories = sport science
Document type = article, proceedings paper, review
172 retrieved

After applying the inclusion and exclusion criteria, 15 studies were retained for further analysis (Figure 8).

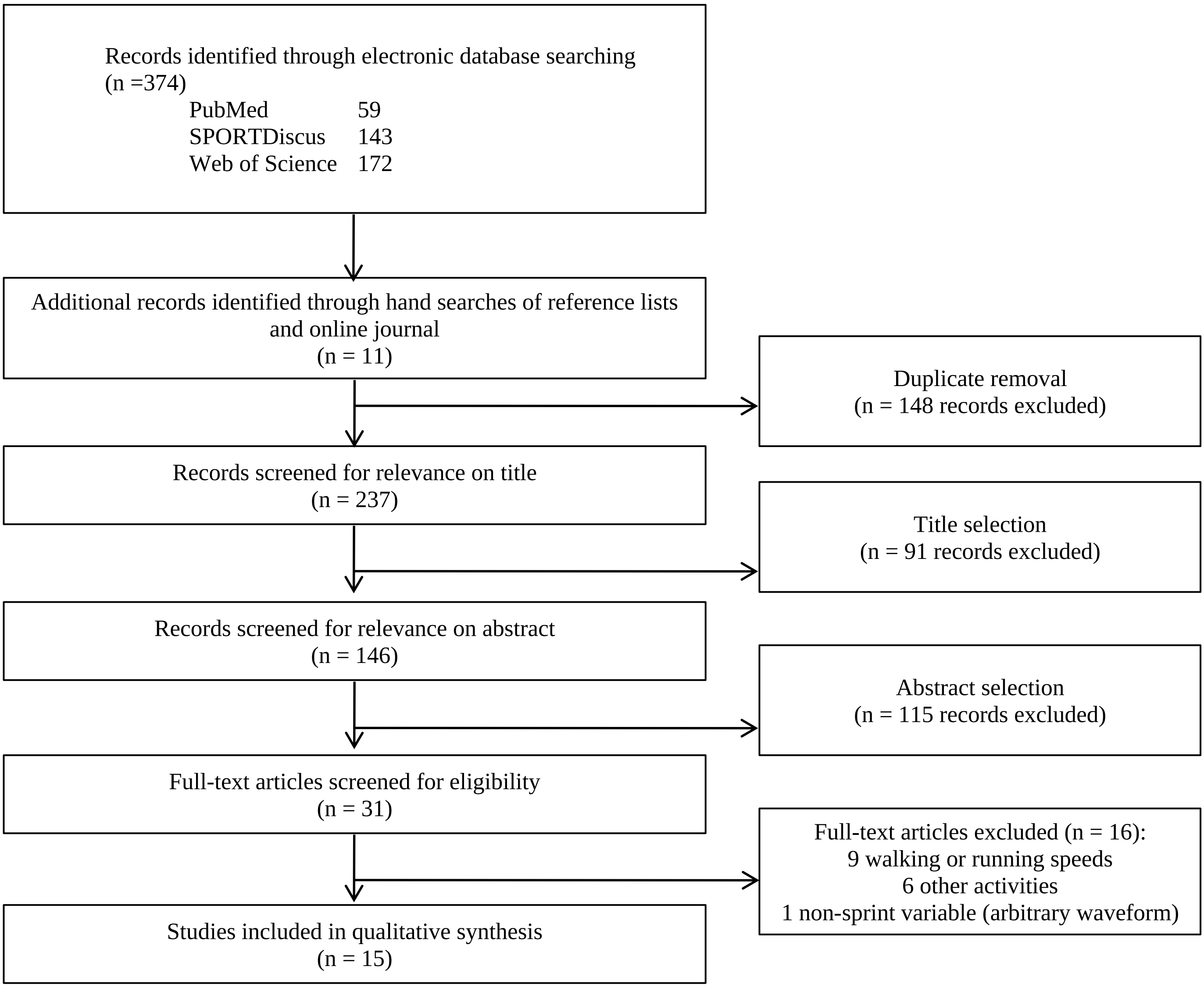


Figure 8. Flow chart of article selection process.

3.2.4 Methodological Quality Score

Methodological quality was assessed using the quality index of Downs and Black (44) modified version (85). A value of 0 or 1 was assigned to the different subcategories of the following items: reporting, external validity, and internal validity. A modified scoring system based on Moens, et al. (85) was used. A total score < 7/17 was low quality, 8-12/17 was moderate, and scores ≥ 13/17 were high quality.

3.2.5 Data Analysis

Validity and reliability acceptance thresholds are commonly set for intraclass correlation coefficient (ICC) and correlation coefficients (r) ≥ 0.70 (83, 137) and coefficient of variation (CV) ≤ 10% (6). However, a recent article by Prescott (112) highlighted the limitations of such an approach. Namely ICCs rarely have a place in which different measurement methods are compared, where inter- and intra-rater variability is assessed or in more general situations where components of variability in measurement are being assessed. Cognisant of these limitations, this article simply states the values published in the respective articles and leaves it to the reader to make their own interpretations as to the statistical and practical utility of the findings.

3.3 Results

3.3.1 Definition of Terms

The variables discussed in this review are defined and clarified as sprint times and sprint velocities; temporal measures; sensor displacement and angular velocity; and forces. The details of the terms within each variable are provided in Table 8.

Table 8. Definition of Terms.

Term	Definition of Variable
Sprint times and sprint velocities	
Average acceleration (m/s^2)	The change in velocity from a given distance by the time taken to travel the distance.
Average velocity (m/s)	The displacement over a given distance by the time taken to travel the distance.
Peak velocity (m/s)	Maximal average velocity between foot contacts (54). Average velocity from maximum velocity to sprint end (111).
V_0 (m/s)	Theoretical velocity for zero horizontal force. As per previous methodology (123).
Temporal measures	
Contact time (ms)	Determined from landing and take-off ground contact of one foot. See individual paper methodologies for details (4, 15, 113, 128).
Stride time (s)	First contact of one foot to the next contact of the same foot.
Sensor displacement and angular velocity	
Medio-lateral axis displacement	The time spent either side of the vertical axis (64).
Trunk displacement angle pick-up phase (°)	Angular orientation of the trunk (from IMU and stereophotogrammetric reference frame) during the phase ranging from block clearing to the upright position See paper methodology for details (14).
Trunk displacement angle whole phase (°)	Angular orientation of the trunk from “set” position block clearing upright position. See paper methodology for details (14).
Shank angular velocity (°/s)	Integration of angular acceleration to provide angular velocity. See paper methodology for details (23).
Forces	
D_{rf} (%/m/s)	Rate of decrease in ratio of forces. As per previous methodology (123).
Horizontal force (N)	Horizontal / anterior-posterior force exerted by the ground on a body in contact with it. Described as Fh as per methodology (132). Described as Fx as per methodology (53).
F_v (N)	Vertical force exerted by the ground on a body in contact with it.
F_{res} (N)	Resultant force from the average value of Fh and Fv (53, 132).
F_y (N)	Medio-lateral force exerted by the ground on a body in contact with it.
F_0 (N)	Theoretical maximal horizontal force the runner can apply at zero velocity. As per previous methodology (123).
P_{max} (W)	Theoretical maximum power developed by the runner. As per previous methodology (123).
Resultant force (N)	Resultant of the tri-axial data from acceleration values (m/s^2) that were converted to force values (154).
S_{fv} (N/m/s)	Slope of linear force-velocity relationship. As per previous methodology (123).

3.3.2 Study Characteristics

The study characteristics of the 15 articles are summarised in Table 9. All the studies included validity measures, five of the studies assessed intraday reliability, while no studies assessed inter-day reliability. Descriptions of populations sampled in the studies included: healthy active subjects, recreational athletes, sprint athletes, national track and field athletes, and rugby players. The number of subjects ranged from three to twenty-eight, with nine of the studies containing less than ten subjects. Over ground sprinting distances ranged from 10 m to 100 m, with two studies analysing the initial take-off steps within a laboratory setting. Sprint analysis ranged from initial take-off steps, from either block or standing starts, to steps during maximum velocity phase, to all steps throughout a 60 m sprint and velocity throughout a 100 m sprint. Eleven of the studies placed the sensor on the back (ranging in position from in-between scapulae to sacrum), with two studies using the shank, and the remaining two studies using a foot or ankle placement. Methods of sensor attachments included memory foam with an elastic belt, housed within a lycra vest, double sided tape and elastic straps, while four studies did not specify their attachment method. Quality assessment scores of the sixteen studies included ranged from 8 to 11, with an average score of 9.9/17, indicating a moderate methodological quality for the studies reviewed (Table 9).

Table 9. Study characteristics of the fifteen articles included in the review.

Study	Sensor placement and attachment method	Sample (age, mass, height, 100 m best time)	Sprint description	Intraday reliability	Validity	Methodology quality
Purcell, et al. (113)	Shank	6 healthy subjects (25.2 years)	3 x over ground sprint (distance and start position unknown) Analysis from steps: 1,3,5,9, and all steps	N	Y	10
Channells, et al. (23)	Shank	6 athletes	Over ground sprint (distance and start position unknown) Analysis from 3 seconds	N	Y	8
Waldron et al. (151)	In-between scapulae Attachment within a pouch in lycra vest	19 male rugby league players (14.7 ± 0.45 years, 1.76 ± 0.65 m, 72.8 ± 10.7 kg)	2 x 30 m over ground sprint. (standing start) 3 min rest between trials	Y	Y	11
Bergamini, et al. (15)	L1 Attached via memory foam and elastic belt	6 amateur athletes (2 females, 4 males)	3 x 60 m over ground sprint indoor track (block start) 10 min rest between trials Analysis 2 strides from 40 m mark	N	Y	9
Bergamini, et al. (15)	L1 Attached via memory foam and elastic belt	5 national track and field athletes (2 females, 3 males, 10.17-11.52 s)	3 x 60 m over ground sprint indoor track (block start) 10 min rest between trials Analysis 2 strides from 40 m mark	N	Y	9
Bergamini, et al. (14)	L2 Attached via memory foam and elastic belt	5 male sprint athletes (23.8 ± 0.8 years; 72.4 ± 3.8 kg; 1.79 ± 0.07 m, 11.21 - 11.50 s)	4 x 12 m over ground indoor laboratory (block start) Analysis block start phase and the first three steps	Y	Y	9
Wundersitz et al. (154)	T2 Attachment within a pouch in lycra vest	12 males and 5 females team sport athletes (21 ± 2 years; 1.82 ± 0.08 m; 78.2 ± 11.6 kg)	4 x 10 m over ground sprint (start position not specified) 1 min rest between trials Step at 5 m analysed	N	Y	11
Alexander, et al. (3)	In-between scapulae Attachment within a pouch in lycra vest	5 male university athletes (20.6 ± 0.5 years; 81.0 ± 10.6 kg)	3 x 40 m over ground sprint (standing start) 5 min rest between trials	N	Y	10
Ammann et al. (4)	Foot Attachment via elastic strap to the laces	7 males. 5 females (25.3 ± 3.2 years, 1.74 ± 0.08 m, 64.8 ± 10.2 kg)	3 x 40 m over ground sprint (start position not specified) 5 min rest between trials	Y	Y	11
Parrington, et al. (111)	Sacrum Attachment via double sided tape	5 sub elite male sprinters	8 x 100 m over ground sprint (start position not specified) Self-selected rest between trials	N	Y	10
Schmidt, et al. (128)	Ankle (lateral border) Attachment via	12 track and field athletes (10 males, 2 females)	3-5 x 60 m over ground sprint (start position not specified)	N	Y	10

	elastic strap		10 min rest between trials Analysis 15 m during maximum velocity			
Bastida Castillo et al. (11)	In-between scapulae Attachment within a pouch in lycra vest	3 athletes	6 x 20 m over ground sprint (start position not specified)	N	Y	9
Gurchiek, et al. (53)	Sacrum Attachment via double sided tape and elastic strap	15 subjects (12 males, 3 females, 23.2 ± 2.1 years; 1.78 ± 0.09 m; 75.5 ± 12.5 kg)	6 x sprint take-off indoor laboratory (standing split stance) Initial two-foot push and first contact step	N	Y	11
Kenneally-Dabrowski et al. (64)	In-between scapulae Attachment within a pouch in lycra vest	13 male rugby union players (23.8 ± 2.4 years; 1.86 ± 0.08 m; 102.3 ± 12.2 kg)	3x 40 m over ground sprint (start position not specified) Analysis of steps between 25m and 32.2 m	N	Y	11
Setuain et al. (132)	L4-L5	16 recreational runners 8 females (26.1 ± 4.4 years; 1.66 ± 0.07 m; 59.8 ± 8.0 kg). 8 males (31.5 ± 6.3 years; 1.77 ± 0.07 m; 78.3 ± 13.0 kg)	4 x 20 m over ground sprint (start position not specified) 90 sec rest between trials Analysis all steps after the initial 2 steps	Y	Y	10
Gurchiek, et al. (54)	Sacrum Attachment via double sided tape and elastic strap	28 collegiate level sprinters and general students (16 males, 12 females, 20.9 ± 2.3 years; 1.73 ± 0.09 m; 71.1 ± 11.7 kg)	3 x 40 m over ground sprint (crouched 4-point start position) 3 min rest between trials	Y	Y	11

3.3.3 Wearable Sensor Specifications and Reference Systems Used

Details of the wearable sensor systems utilised and their respective specifications can be found in Table 10. Nine of the studies used an IMU, five studies used only a tri-axial accelerometer, and one study used a dual-axial accelerometer for data collection. Accelerometer and gyroscope capability ranged from ± 6 g to ± 24 g and ± 500 deg/s to ± 2000 deg/s, respectively. Sample rates ranged from 100 Hz to 1000 Hz. Many different post-processing techniques were applied, including noise reduction and sensor fusion algorithms. Moving averages (3 to 40 point) and low pass Butterworth filters (10 to 100 Hz) were the most common noise reduction algorithms applied. Sprint performance parameters calculated include sprint times and velocities, temporal measures, sensor displacement and angular velocity, and forces. Contact times were determined using minimum and maximum peaks in the acceleration signal, with some studies utilising a ‘critical threshold’. Average accelerations were determined using moving averages, peak velocities were calculated by integration of the horizontal acceleration signal; while Setuain et al. (132) integrated external reference systems to determine linear velocities. Double integration of the acceleration signal calculated angular displacements, with the most common filters used being Kalman and Madgwick. GRF were derived using Newton’s Law/inverse dynamics method, coupled with quaternion-based rotation matrices and the instantaneous centre of mass acceleration. Six different reference systems were used for validity comparison. Six studies used force plate technology, four studies used timing lights, three studies used high-speed video camera, one study used motion capture, one study used infrared photocells, and one study used a laser gun.

Table 10. Wearable sensor systems specifications and reference systems.

Study	Sensor type	Sensor hardware specification	Reference system	Synchronisation method	Variables	Post Processing
Purcell, et al. (113)	Tri-axial accelerometer (Analog Devices ADXL321)	Tri-axial accelerometer (± 18 g) Sampled at 250 Hz	One force platform (Kistler piezoelectric force plate) Sampled at 1000 Hz	Synchronisation pulse	Contact time	Minimum in the x axis acceleration for initial contact. Minimum and max in x and z axis accelerations for toe-off, with the mean used define the end of contact time.
Channells, et al. (23)	Dual-axial accelerometer (Analog devices ADXL321)	Dual-axial accelerometer (± 18 g) Sampled at 250 Hz	One high-speed camera	Synchronised but no details	Shank angular velocity	Low pass 100 Hz RC filter Integration and double integration of the tangential data provided the angular velocity
Waldron et al. (151)	Tri-axial accelerometer (GPSports, SPI-Pro, Canberra, Australia)	Tri-axial accelerometer (± 6 g) Sampled at 100 Hz	Timing gates (Brower Timing Systems, Draper, UT) at 0.6 m height	No details provided	Peak velocity Velocity at 10 m, 20 m, 30 m	No details provided
Bergamini, et al. (15)	IMU (FreeSense, Sensorize, Italy)	Tri-axial accelerometer (± 6 g) and a tri-axial gyroscope (±500 deg/s) Sampled at 200 Hz	6 adjacent in ground force platforms (Z20740AA, Kistler, Switzerland; total surface: 6.6×0.6 m) Sampled at 200 Hz	Synchronisation strike on force plate	Contact time Stride time	Noise reduction with wavelet based smoothing. Min and max of acceleration signal to determine ground contact phases. Identified key features in raw data Gyroscope-based algorithms
Bergamini, et al. (15)	IMU (FreeSense, Sensorize, Italy)	Tri-axial accelerometer (± 6 g) and a tri-axial gyroscope (± 500 deg/s) Sampled at 200 Hz	One high-speed camera (Casio Exilim EX-F1, Japan,), 5 m away from the lane. Sampled at 300 Hz (70 Hz Butterworth filter)	No synchronisation performed	Contact time Stride time	Noise reduction with wavelet based smoothing Algorithms derived from the above force data.
Bergamini, et al. (14)	IMU (FreeSense, Sensorize, Italy)	Tri-axial accelerometer (± 6 g) and a tri-axial gyroscope (± 500 deg/s)	9-camera stereophotogrammetric system (Vicon MX3, Oxford, UK) Sampled at 200 Hz	Synchronisation via sudden standing trunk flexion-extension.	Trunk displacement angle	Noise reduction with low-pass filter (40-point moving average) Adaptive Kalman filter Filter ratios altered for different sprint phases (i.e. sprint start), and Ad Hoc trials

		Sampled at 100 Hz				to determine constants Quanternion-based Initial offset was needed for every subject
Wundersitz et al. (154)	Tri-axial acceleration sensor (Bosch, BMA150, Stuttgart, Germany)	Tri-axial acceleration sensor (± 8 g) Sampled at 100 Hz	In-ground force plate (BP600900, Advanced Mechanical Technology Inc., Watertown, USA) Sampled at 100 Hz (10 Hz data smoothed)	Synchronisation via video software to identify ground contact	Crania-caudal force Resultant force	Butterworth filter 4th order dual pass at 10, 15, 20, 25 Hz
Alexander, et al. (3)	Tri-axial accelerometer (GPSports, SPI-HPU, Canberra, Australia)	Tri-axial accelerometer (± 16 g) Sampled at 100 Hz	Dual-beam timing gates (Swift, Brisbane, Australia)	Synchronisation through time stamps of sensor and camera	Average acceleration at 0-10 m and 10-20 m	3, 10 point moving average Start was identified as the instant from the minimum anterior-posterior acceleration trace that increased above zero. The sprint time, measured by the timing gates, was added to the starting point to signify the end of the trial.
Ammann et al. (4)	IMU (InvenSense, Inc., San Jose, CA, USA)	Tri-axial accelerometer (± 16 g), a tri-axial gyroscope, and a tri-axial magnetometer Sampled at 1000 Hz	One high-speed camera (HSC Marathon Ultra) Sampled at 1000 Hz	No details provided	Contact time	Min and max of acceleration signal to determine ground contact phases
Parrington, et al. (111)	IMU (IMeasureU Blue Thunder IMU, Auckland, New Zealand)	Tri-axial accelerometer (± 16 g), tri-axial gyroscope (2000 deg/s), and a tri-axial magnetometer (± 1200 deg/s) Sampled at 500 Hz	Laser gun (LAVEG Sport, Jenoptik, Germany) Sampled at 100 Hz	Synchronisation method was start and stop times in IMU software	Peak velocity Velocity at every 10 m from 0 to 100 m	Horizontal accelerations were isolated, integration to calculate velocity, and further integration used to calculate displacement. Madgwick Filter Rotation matrices (to get acceleration), with double integration to get displacement. Broken into piecewise functions for sprint phases
Schmidt, et al. (128)	IMU	Tri-axial accelerometer (± 16g range) and tri-axial gyroscope (16 bit	OptojumpNext photocell system (Microgate, Bolzano, Italy,)	No details provided	Contact time	No filtering of raw data Peak detection method with critical threshold (usually 5g) and min and max of acceleration signal to determine ground

		and ± 1000 deg/s range) Sampled at 1000 Hz	Sampled at 1000 Hz			contact Reset of analog and digital signal after each step to avoid drift
Bastida Castillo et al. (11)	IMU (WIMU PRO, RealTrack System, Almeria, Spain)	Tri-axial accelerometer (± 16g range), tri-axial gyroscope (±2000 deg/s range), and a tri-axial magnetometer Sampled at 100 and 1000 Hz	Timing gates (ChronoJump, Spain)	No details provided	20 m time	IMU software used an atomic clock and made automatic selection from mark to mark.
Gurchiek, et al. (53)	IMU (Yost Data Logger 3-Space Sensor, YEI Technology, Portsmouth, OH, USA)	Tri-axial accelerometer (± 24 g) and a tri-axial gyroscope (± 2000 degree/s) Sampled at 450 Hz	Force plate (AMTI, Watertown, MA) Sampled at 1000 Hz	Synchronisation using cross-correlation data obtained from two counter movement jumps prior to the movement trials	Step-average force and Instantaneous force for F_x, F_y, F_v, F_{res}	Low pass filter 30 Hz Quanternion-based Rotation matrices to obtain IMU estimate of force in the force plate frame.
Kenneally-Dabrowski et al. (64)	Tri-axial accelerometer (GPSports, Canberra, Australia)	Tri-axial accelerometer (± 16 g) Sampled at 100 Hz	8 contiguous force plates (Kistler, Amherst, MA, USA) Sampled at 1000 Hz	No details provided	Medio-lateral displacement Stride time	Min and max of acceleration signal to determine ground contact phases Butterworth low pass filter at 100 Hz.
Setuain et al. (132)	IMU (MTx, 3DOF Human Orientation Tracker, Xsens Technologies B.V. Enschede, Netherlands)	Tri-axial accelerometer, a tri-axial gyroscope, and a tri-axial magnetometer Sampled at 120 Hz	10 m force platform system (Raute Precision, Lahti, Finland) Sampled at 1000 Hz	Synchronisation of time via two pulse signals	F_h, F_v, F_0, V_0 P_o, S_{fv}, D_{rf}	Noise reduction with 5 m splits, using least-squares fit was used to estimate bias in acceleration, and then velocity based on corrected acceleration signals (with bias). For variables of interest, integration of the horizontal acceleration signal to get horizontal velocity and then integrate that velocity to get distance covered. Instantaneous horizontal and vertical GRF opponents were calculated using instantaneous centre of mass acceleration

						Sensor Orientation: an on-board algorithm was used to produce orientation data - the output is all acceleration signal expressed in a track-fixed reference frame (earth reference frame).
Gurchiek, et al. (54)	IMU (Yost Data Logger 3-Space Sensors, YEI Technology, Portsmouth, OH, USA)	Tri-axial accelerometer (± 24g range), tri-axial gyroscope (± 2000 deg/s range), and a tri-axial magnetometer Sampled at 450 Hz	Timing gates (Brower Timing Systems, Draper, UT)	Synchronisation of frames with the initial forward movement of the IMU and of hand touch coming off the touch sensor	Peak velocity Velocity at every 10 m from 0 to 40 m	Low pass filter at 1 Hz Kalman filter

D_{rf} - rate of decrease in ratio of forces; F_h - horizontal force; F_0 - horizontal force at zero velocity; F_{res} - resultant force; F_v - vertical force; F_x - anterior-posterior force; F_y - medio-lateral force; GRF – ground reaction force; IMU - inertial measurement unit; P_{max} - maximum power; S_{fv}- Slope of linear force-velocity relationship; V_0 - velocity for zero horizontal force

3.3.4 Validity and Reliability Measures

The summarised results of the validity and reliability of wearable sensors during sprinting can be found in Table 11. A wide variety of outcome variables were used in the assessment of validity and reliability: sprint times, peak and average velocity, step variables, segment angular displacement and velocities, GRF and maximum power. Moreover, a range of statistical measures were used which included: Bland-Altman limits of agreement (LoA), CV, ICC, r, root mean square error (RMSE), mean difference and mean error.

Higher levels of validity were found in contact time (ICC $\geq$ 0.80, r $\geq$ 0.99, LoA bias-8 to 25 ms), stride time (LoA bias 25 ms), trunk angular displacement (r $\geq$ 0.99), resultant force (r $\geq$ 0.76), vertical and horizontal force (r = $\geq$ 0.88), and V_0 F_0, P_{max}, and S_{fv} (r $\geq$ 0.81). Mixed validity findings occurred in peak and average velocity (r = 0.32-0.95) and resultant force (r = 0.35-0.76). Lower levels of validity were found in crania-caudal force (r = 0.12-039), instantaneous forces (r = -0.24 to 0.64), medio-lateral GRF (r = 0.35), and rate of decrease in ratio of forces (r = 0.33). Regarding reliability, low levels of CV were found in peak velocity (CV $\leq$ 1%, LoA bias 0.00 $\pm$ 0.8 km/h), average velocity (CV $\leq$ 3%, ICC $\geq$ 0.91), contact time (CV $\leq$ 4%, ICC $\geq$ 0.91), trunk angular displacement (r $\geq$ 0.99), and theoretical measures of V_0, F_0, and P_{max}, (ICC $\geq$ 0.88). However, lower levels of reliability results were in D_{rf} (r = 0.66).

Table 11. Validity and reliability results from the wearable sensors.

Study	Validity/reliability	Variables	Sensor mean	Reference system mean	Absolute reliability			Relative reliability	
					CV (%)	LoA bias (95%)	RMSE	ICC (95% CI)	*r* (95 % CI)
Purcell, et al. (113)	Concurrent validity (accelerometer vs. force plate)	Contact time (ms) Step 1 Step 3 Step 5 All steps				 -8 ± 9 -2 ± 5 0 ± 1 1 ± 1			 0.951 0.967 0.991 0.997
Channells, et al. (23)	Concurrent validity (accelerometer vs. high-speed camera)	Shank angular velocity (°/s)					89.7-143.2 (5.0-9.1%)		
Waldron et al. (151)	Concurrent validity (accelerometer vs. timing gates) Intraday reliability (accelerometer)	10 m velocity (km/h) 20 m velocity (km/h) 30 m velocity (km/h) 10 m velocity (km/h) 20 m velocity (km/h) 30 m velocity (km/h) Peak velocity (km/h)	14.5 ± 1.9 18.3 ± 1.7 20.7 ± 1.4	16.5 ± 1.2 20.5 ± 1.2 22.7 ± 1.2	9.81 8.54 6.61 2.06 1.92 2.02 0.78	2.05 ± 3.62 2.19 ± 3.34 2.01 ± 2.18 0.05 ± 1.05 -0.05 ± 1.17 -0.09 ± 0.84 0.00 ± 0.80			
Bergamini, et al. (15)	Concurrent validity (IMU vs. force plate)	Contact time (ms) Stride time (ms)	125 ± 15 495 ± 40			25 25			
Bergamini, et al. (15)	Concurrent validity (IMU vs. high-speed camera)	Contact time (ms) Stride time (ms)	105 ± 15 455 ± 15			25 25			
Bergamini, et al. (14)	Concurrent validity (IMU vs. motion capture system) Intraday reliability (IMU)	Trunk displacement angle whole phase (°) Trunk displacement angle pick-up phase (°) Trunk displacement angle whole phase (°) Trunk displacement angle pick-up phase (°)					3 ± 2 (4%) 3 ± 3 (5%) 3 ± 2 (5%) 3 ± 2 (6%)		0.994 ± 0.013 0.995 ± 0.015 0.998 ± 0.002 0.998 ± 0.001
Wundersitz et al. (154)	Concurrent validity (accelerometer vs. force plate)	Crania-caudal force (N) Resultant force (N)	1582 ± 408 2194 ± 317	1731± 245 1755± 253	15-16.2 11.7-16.4				0.12-0.39 0.35-0.76

Alexander, et al. (3)	Concurrent validity (accelerometer vs. timing gates)	0-10 m average acceleration (m/s^2)							
		Raw output			22.49	1.11 (-1.67, 3.90)			-0.447
		3 point moved average			21.41	1.26 (-1.45, 3.97)			- 0.403
		10 point moved average			20.17	1.53 (-1.13, 4.13)			-0.371
		10-20 m average velocity (m/s)							
		Raw output			20.22	2.87 (-1.87, 7.61)			-0.516
		3 point moved average			20.23	2.88 (-1.88, 7.63)			-0.526
		10 point moved average			20.01	2.91 (-1.81, 7.64)			-0.531
Ammann et al. (4)	Concurrent validity (IMU vs. high-speed camera)	Contact time (ms)	118.3 ± 11.6	117.5 ± 9.0				0.808 (0.653–0.894)	
	Intraday reliability (IMU)	Contact time (ms)			2.9-3.8			0.911–0.960	
Parrington, et al. (111)	Concurrent validity (IMU vs. laser)	Peak velocity (m/s)							0.92
		0-10 m velocity (m/s)							0.32
		10-20 m velocity (m/s)							0.85
		20-30 m velocity (m/s)							0.89
		30-40 m velocity (m/s)							0.90
		40-50 m velocity (m/s)							0.92
		50-60 m velocity (m/s)							0.93
		60-70 m velocity (m/s)							0.95
		70-80 m velocity (m/s)							0.95
		80-90 m velocity (m/s)							0.93
		90-100 m velocity (m/s)							0.86
Schmidt, et al. (128)	Concurrent validity (IMU vs. optojump)	Contact time (ms)		124.6 ± 10.6		-2.5 (-11.8, 6.8)			
Bastida Castillo et al. (11)	Concurrent validity (IMU vs. timing gates)	20 m time (s)							
		100 Hz IMU	5.04 ± 0.20	5.04 ± 0.20				1.00	1.00
		1000 Hz IMU	5.14 ± 0.25	5.14 ± 0.25		0.06 (-2.9, 4.1)		1.00	1.00
Gurchiek, et al. (53)	Concurrent validity (IMU vs. force plate)	Step-average force							
		F_x (N)				2.52 (77.5, 77.5)	37.70		0.89
		F_y (N)				-15.9 (-144.2,	66.30		0.35

						112.3)			
		F_v (N)				-34.1 (-171.8, 103.7)	54.19		0.88
		F_{res} (N)				-29.7 (-163.8, 104.4)	70.22		0.90
		Instantaneous force							
		F_x (N)					400.1±219.6		0.64 ± 0.15
		F_y (N)					406.7±260.8		-0.24 ± 0.31
		F_v (N)					368.2±210.7		0.50 ±0.30
		F_{res} (N)					466.3±282.0		0.49 ± 0.29
Kenneally-Dabrowski et al. (64)	Concurrent validity (accelerometer vs. force plate)	Medio-lateral axis displacement				0.189 (-0.286, 0.663)			0.088
		Stride time (s)				-0.26 (-0.09, 0.039)			-0.177
Setuain et al. (132)	Concurrent validity (IMU vs. force plate)	F_h (N)	119 ± 92	116 ± 105		(-100.8, 93.0)			0.87 (0.87,0.87)
		F_v (N)	661 ± 135	670 ± 145		(-126.5, 144.2)			0.88 (0.88,0.88)
		F_0 (N)	383 ± 110	391 ± 103		(-42.7, 57.9)			0.97 (0.96,0.98)
		V_o (m/s)	8.61 ± 0.85	8.42 ± 0.69		(-1.28, 0.80)			0.76 (0.71, 0.81)
		P_{max} (W)	873 ± 246	779 ± 241		(-234.2, 89.9)			0.90 (0.88, 0.91)
		S_{fv} (N/m/s)	-44.6 ± 12.7	-46.2 ± 10.7		(-9.64, 6.40)			0.93 (0.91, 0.94)
		D_{rf} (%/m/s)	-6.32 ± 1.08	-5.76 ± 0.68		(-1.38, 2.50)			0.33 (0.26, 0.41)
	Intraday reliability (IMU)	F_0 (N)				(-97.46, 61.84)			0.93 (0.79, 0.98)
		V_o (m/s)				(-0.58, 0.51)			0.88 (0.65, 0.96)
		P_{max} (W)				(-175.2, 105.0)			0.95 (0.83, 0.98)
		S_{fv} (N/m/s)				(-9.34, 13.01)			0.89 (0.70, 0.97)
		D_{rf} (%/m/s)				(-2.03, 2.36)			0.66 (0.20, 0.88)
Gurchiek, et al. (54)	Concurrent validity (IMU vs. timing gates)	Peak velocity (m/s)	8.50 ± 1.24	8.30 ± 1.09					
		0-10 m velocity (m/s)	7.49 ± 0.86	7.73 ± 0.89					
		10-20 m velocity (m/s)	8.11 ± 1.09	8.16 ± 1.02					
		20-30 m velocity (m/s)	8.42 ± 1.24	8.29 ± 1.08					
		30-40 m velocity (m/s)	8.50 ± 1.24	8.30 ± 1.09					
	Intraday reliability (IMU)	Peak velocity (m/s)				-0.12 (-0.59, 0.34)			
		0-10 m velocity (m/s)				-0.25(-1.18, 0.68)			
		10-20 m velocity (m/s)				-0.05 (-1.30, 1.20)			
		20-30 m velocity (m/s)				0.13 (-1.32,			

		30-40 m velocity (m/s)				1.59) 0.20 (-1.25, 1.64)			

CV – coefficient of variance; CI – confidence interval; D_{rf} - rate of decrease in ratio of forces; F_h - horizontal force; F_p - horizontal force at zero velocity; F_{res} - resultant force; F_v - vertical force; F_x– anterior-posterior force; F_y– medio-lateral force; ICC - intraclass correlation coefficient; LoA - limits of agreement; P_{max} - maximum power; r - Pearson's correlation coefficient; RMSE – root mean square error; S_{fv}- Slope of linear force-velocity relationship; V_o - velocity for zero horizontal force

3.4. Discussion

The purpose of this article was to review the validity and reliability of inertial sensors to referenced systems during sprinting. From the studies reviewed, it was observed that a wide range of sprint performance variables, as well as validity and reliability measures were used, when comparing different sensor placements with different criterion reference systems. The reader needs to be cognisant that due to these methodological differences, it is difficult to interpret anything with certainty, the factors responsible for this uncertainty warrant consideration. Nonetheless, the following sections attempt to lend some insight into the value and utility of these sensors in quantifying sprint performance under the following section titles: sprint times and sprint velocities; temporal measures; sensor displacement and angular velocity; and forces.

3.4.1 Measures of Sprint Times and Sprint Velocities

3.4.1.1 Validity

Higher levels of validity were found in 20 m sprint times (ICC ≥ 0.99, r ≥ 0.99, LoA bias 6 ± 1.8 ms) and V_0 (r > 0.80) (11, 132). Validity findings ranged in peak and average velocity (r = 0.32-0.95) (2, 96). Additional measures of validity not reported in the Table 11 were mean differences: 1.5 ± 2.4% in peak velocity, 0.1 ± 10.1% in 0-10 m velocity, 9.1 ± 2.9 % in 10-20 m velocity, and < 5.3 ± 4% in all other 10 m velocity phases up to 100 m (111), and mean absolute error of 0.63 m/s (7.8%) in peak velocity (54).

Researchers used sensor placements of in-between scapula (3, 11, 151), sacrum (54, 111) or lumbar (132). There appears no consistent trend as to which placement was found more valid than another. The reasons for these variations have been attributed to the attachment methods (straps, tape, vest pocket), which may have influenced the accuracy of the findings through increased external noise due to the sensor being vibrated, or hit against the body during rapid sprint movements, especially during the start of a sprint. The sampling frequencies from the sensors used in these studies, ranged from 100 Hz to 1000 Hz. Though validity measures were found with lower sampling frequencies (~100 Hz), it would seem sampling frequency of ≥ 500 Hz enabled a greater level of validity. This is highlighted by Bastida Castillo, et al. (11) who used two different IMU sampling rates (100 Hz and 1000 Hz) on different days. Though levels of agreement in sprint times were found with both sampling rates, the higher frequency slightly underestimated times (mean difference = -0.001 to -0.002 s), while the lower sample frequency slightly overestimated, with a larger range (mean difference = 0.000 to 0.009 s). Of note, this study used wireless transmissions from light gates to trigger the inertial sensor timing subsystem. This enables timing of specific distance check points to be incorporated into IMU data. The results reported by this study validate the timing subsystems of each technology, but do not solve any challenges presented by sprint assessment. Therefore, caution is required when interpreting the validity of 20 m sprint times from wearable sensors based on this study.

Four research groups (3, 11, 54, 151) used timing gates as the reference systems, another group used laser (111), and one group of researchers used a force plate (132). Though measures against the laser and force plate were found be to valid, mixed validity results were found compared to the timing gate systems. For example, peak velocity was found to be valid (mean difference 1.5%, r = 0.92) against laser (111), whereas a systematic difference (mean difference 7.8%) was found in peak velocity measures compared to timing gates (54). Differences in sampling rates between reference systems and sensors, and methods of handling of the raw data may have contributed to the disparity in results. Moreover, discrepancies in findings between the studies may relate to the different sensors (IMU and accelerometer) used. Of note, different sprint variables and validity measures were used between studies, therefore, limiting the scope of these comparisons.

The validity of velocity improved after the initial start and early acceleration phase of the sprint. This is highlighted by Parrington et al. (2016) who reported lower levels of correlation ($r = 0.32$) during the initial 10 m, though beyond this distance higher levels of correlation agreement ($r > 0.85$) were found for all distance markers up to 100 m. The authors also reported that the first split (0-10 m) had the highest variance (SD ± 10.1%), whilst the second split (10-20 m) had the highest per cent difference between the devices (9.1%). Moreover, Alexander, et al. (3) found there was a smaller correlation ($r = -0.32$ to -0.47) during 0-10 m compared to 10-20 m ($r = -0.52$ to -0.53), suggesting that validity improves as the sprint distance increases. Similarly, Gurchiek, et al. (54) found no systematic differences between the IMU and photocell estimates of average velocity for the final two 10 m splits (20-30 m and 30-40 m), whereas, the average velocity for the first two 10 m splits was significantly different. These differences in the start and early acceleration phase may be attributed to the variability associated with this type of motion (rapid change in body position), and the algorithm used to curve fit this phase not being fully representative of individual sprint performance. Moreover, a limitation of the study by Alexander, et al. (3) relates to compensation of axis orientation due to accelerometer having its own axis frame of reference affecting the validity comparison.

2.4.1.2. Reliability

Reliability levels were reported for peak velocity (CV ≤ 1%, LoA bias 0.00 ± 0.8 km/h), average velocity (CV ≤ 3%, and V_0 (ICC ≥ 0.88, LoA 95% range −0.58 to 0.51 m/s) (132, 151). Waldron, et al. (151) reported peak velocity (CV = 0.78%, 95% LoA bias 0.00 ± 0.08 km/h) and velocity at all distance marks 10-30 m (CV = < 3%, LoA bias -0.09 ± 1.17 km/h) reliable. Setuain et al. (2017)

also measured sprint performance over a short distance (20 m), and reported coefficients (ICC ≥ 0.88, LoA 95% range -0.58 to 0.51 m/s) with respect to the reliability of V_0. Gurchiek et al. (2018) reported greater reliability in 0-10 m (LoA bias -0.12m/s) and 30-40 m (LoA bias 0.13 m/s) average velocity compared to 10-20 m (LoA bias -0.25 m/s)). Possible reasons for differences may relate to individual changes in velocity throughout 10-20 m as subjects start from 0 m/s and may attain similar max velocity.

3.4.1.3. Summary

In summary, higher levels of validity were found in 20 m sprint times and V_0, with mixed levels of validity found for peak and average velocity. However, peak velocity, average velocity, and V_0 were all reported to be reliable. Variables are less accurate during the start of the sprint and early acceleration phase (< 20 m), most likely due to the rapid changes in body and limb positions causing a greater amount of external noise and complications with sensor orientation. Moreover, the validity and reliability of the sprint measures seem to be affected by the sampling frequency and reference system used.

3.4.2 Temporal Measures

3.4.2.1. Validity

Levels of validity were reported for contact time (r ≥ 0.99, ICC ≥ 0.8, LoA bias -8 to 25 ms and stride time (LoA bias 25 ms) (4, 15, 113, 129). Additional measures of validity not reported in Table 11 were mean difference of 4.3 ms (3.4%), and systematic error of -2.5 ± 4.8 ms in contact time (129), and mean difference of 0.1 ± 6.7% and systematic bias of 0.4 ms in contact time (4).

Three researcher groups used sensor placements of the lower leg (4, 113, 129), with one group using the lumbar (15), and one group using in-between the scapulae (64). The highest validity was associated with lower leg and lumbar placements, whereas the in-between scapulae placement was found to be problematic. The reasons for these variations may be attributed to the sensor is further away from the impact point (the foot), and attachment issues within the vest affecting shock attenuation which may reduce accelerations recorded, resulting in lower validity levels. The sampling frequencies used in these studies ranged from 50 Hz to 1000 Hz, with improved validity found with ≥ 200 Hz.

Three groups (15, 64, 113) used force plates as the reference systems, with two groups using a high-speed camera (4, 15) and one group using a Optojump photocell system (129). Though measures against the photocell system and high-speed camera were found to have higher validity, mixed results were found for the force plate comparisons. Discrepancies in findings between the studies in step detection validity may relate to the different phases of the sprint being measured (<10 m, 25-32 m, and 40 m). However, these differences may also relate to the previously mentioned sensor positions with Kenneally-Dabrowski et al. (2017) using an in-between scapula placement and reporting a non-significant relationship (r = -0.177).

3.4.2.2. Reliability

Reliability levels were reported for contact time (CV ≤ 4%, ICC ≥ 0.91) from one group (4). The authors noted that small differences in velocity, that occur naturally between individuals and trials, reflect in the variability of the measures. As such, the authors proposed that sensors may be used to measure contact times, whereby measured changes reflect true changes (4).

3.4.2.3. Summary

In summary, it appears that: 1) the more distal the lower-limb sensor is located (i.e. the closer the sensor was to the foot); and, 2) the higher the sample rate, the more accurate the detection of temporal step variables. Contact times were found to have higher validity and reliability, whilst validity was also found in measures of stride time.

3.4.3. Sensor Displacement and Angular Velocity

3.4.3.1. Validity

Levels of validity were found in trunk angular displacement (r ≥ 0.99) and shank angular velocity (RMSE <10%) (14, 23). Additional measures of validity not reported in the Table 11 were mean differences in trunk angular displacement at the following identification points: on your marks phase 1 ± 1°, set phase 1 ± 1°, transition phase 4 ± 4°, pick-up phase 9 ± 6° (14).

Sensor placements varied from in-between scapula (64), lumbar (15), and shank (23). It would seem that the strongest validity has been associated with lumbar sensor placement, whereas the in-between scapulae placement was found problematic. Sensors placed closer to the area of interest appear to result in a higher level of validity i.e. lumbar placement for trunk displacement, and shank placement for shank velocity. The sampling frequencies used ranged from 100 Hz to 250 Hz, with higher levels of validity found when ≥ 200 Hz were used. However, as different variables were measured, the comparisons in placement and sampling frequency is limited and conclusions should be made with caution.

Two groups used high speed cameras (14, 23), and one group used force plates (64) as reference systems. Analysis from a block start and initial three steps, revealed high levels of validity (r = 0.994, RMSE = 4%), and low levels of disparity (<10°) in trunk angular displacement with a lower back sensor placement (14). The authors also reported small RMSE errors (1 ± 1°) during on your marks and set phases of a sprint, though the errors were larger for the set (4 ± 4°) and transition comparisons (9 ± 6°). Channells, et al. (23) used a tri-axial accelerometer, attached to the shank, and found that the sensor can accurately measure angular velocity with RMSE <10%. Though measures against the high-speed cameras were found to have high levels of validity, Kenneally-Dabrowski et al. (64) reported minimal association was found between sensor (in-between scapulae placement) and force plate data in medio-lateral axis step displacement (correlation 0.088) during the maximum velocity phase. As previously mentioned, given the small amount of literature as well as the variety of assessments, it is uncertain how the reference systems that were used may have affected the validity.

3.4.3.2. Reliability

Only Bergamini, et al. (14) reported reliability (r = 0.998, RMSE = 5%) in trunk angular displacement with a lower back sensor placement that was recorded during the initial start and three steps (14).

3.4.3.3. Summary

In summary, sensors sampled at ≥ 200 Hz, and placed closer to the area of measurement, result in higher validity when quantifying displacement measures. Body segment displacement and velocity appears to result in greater validity, as compared to step axis displacement. However, as only two studies quantified displacement, across different sites, with minimal validity and reliability measures, clearly more research is required.

3.4.4. Forces

3.4.4.1. Validity

Levels of validity were found for resultant peak force (r ≥ 0.76), vertical and horizontal force (r ≥ 0.88), and F_0, P_{max}, and S_{fv} (r ≥ 0.94) (53, 132, 154).

Researchers have used sensor placements in different positions on the back: T2 (154), lumbar (132), and sacrum (53). The highest validity was associated with sensor placement closer to the centre of mass (lumbar and sacrum), whereas the T2 placement resulted in mixed levels of validity, depending on the measurement of interest. Similar to temporal measures, the reasons for these variations may be attributed to differences in sensor placement and attachment i.e. the sensors further away from the impact point (the foot) and housed in lycra vest appear to result in lower validity. Moreover, Wundersitz, et al. (154) noted that the sensor's location on the upper body may promote misalignment of the crania-caudal axis from the global vertical axis, and further consideration of device location and harness design to limit unwanted movement is required.

The sampling frequencies used in these studies to quantify the variables of interest ranged from 100 Hz to 450 Hz, with improved validity found with ≥ 120 Hz. Though lower levels of validity were found with sampling at 100 Hz, the placement of the sensor used by Wundersitz, et al. (154) may have attributed these findings. All three groups used force plates as the reference systems for comparison. However, though Setuain, et al. (132) and Gurchiek, et al. (53) had force plates sampling at 1000 Hz, Wundersitz, et al. (154) had force plate sample rate of 100 Hz. Therefore, the lower sampling rate with both the sensor and force plate, coupled with the sensors placement, may have contributed to the lack of validity found from this group. Moreover, the highest level of validity ($r = 0.76$) from this group was found in resultant forces when data smoothing at 10 Hz positively affected the resultant accelerometer data.

Of note, similar to previous variables, it seems that the phase of the sprint measured can impact on the validity of force measures. From the initial push from both feet and first step from a standing start, GRF and resultant forces were compared across measurement modalities in two ways: instantaneous sensor forces compared to reference sampled GRF and step-average GRF by Gurchiek, et al. (53). Levels of validity were higher for all step-average GRF values ($r > 0.89$) except for the medio-lateral component (Fy) of GRF ($r = -0.35$). Levels were lower for instantaneous values of GRF ($r > 0.49$), with medio-lateral GRF (-024 ± 0.31) found to have the greatest variance (53). From the 5 m mark, Wundersitz, et al. (154) reported mixed agreement levels between systems in crania-caudal forces ($r = 0.12$-0.39) and in resultant forces ($r = 0.35$-0.76). In contrast to initial step measures in the other two studies, analysed steps during a 20 m sprint (the intial two take-off steps were not analysed) found the vertical and horizontal GRF values measured with both systems were correlated ($r = 0.88$ for both GRF vectors).

3.4.4.2. Reliability

Reliability was reported for F_0, P_{max}, and S_{fv} ($ICC \geq 0.88$) (132). Though the D_{rf} was found to result in lower levels of reliability ($ICC = 0.66$). Setuain, et al. (132) noted that the convergence of forces at the centre of mass resulted in greater variability in the D_{rf} obtained from the IMU, thus lower levels of reliability. Furthermore, the aforementioned forces depended on the sprinter's technique and/or ability to apply horizontal GRF during the sprint at increasing velocities, therefore, the error in rate of decrease in ratio of forces may be associated with individual differences in sprint mechanics. This highlights the importance of sensor placement, particularly as the centre of mass is moved abruptly during the start of a sprint, with more research needed to understand the effect of placement and its impact on data collection.

3.4.4.3 Summary

In summary, resultant peak force, vertical and horizontal force, and F_0, P_{max}, and S_{fv} were found to have higher levels of validity. The D_{rf} had lower validity and reliability, while the medio-lateral component of force was also found to have low validity. Similar to previous measurement variables, it appears that measures of force are less accurately collected during the start and early acceleration phase of the sprint, possibly due to the changing body position and changing force profile. Greater accuracy was found with higher sampling frequencies (≥ 100 Hz) and sensor placement closer to the centre of mass, though different measures were collected between studies, warranting caution in interpreting these findings.

3.4.5 Limitations

A limitation of this review relates to multiple differences in methodologies between studies. Essentially there are a large number of variables that are likely to impact data collection and thus each variable has not been isolated and assessed for its contribution. Thus, variations in methodologies impact multiple variables, making critical analysis on any one variable problematic. Specifically, differences in the placement, sampling frequencies and specification of the wearable sensor devices makes definitive conclusions problematic. Moreover, a range of reference systems were used, which differed in set-up and data capture capabilities. Differences in measure of sprint performance also varied between studies. A range of different statistical measures were used, though no inter-day reliability measures have been completed. Moreover, the use of correlations instead of ICCs in several studies and no measures of absolute consistency/typical error highlights a statistical limitation in the research reviewed. Therefore, caution is warranted when interpreting the findings and this article simply states the values published in the respective articles and leaves the reader to make their own interpretations of the findings.

3.4.6 Practical Applications and Future Considerations

Though a clear understanding of the validity and reliability of inertial sensors has yet to be found, some general recommendations can be made. Inertial sensors can be used to measure the following variables with some confidence: contact times, resultant peak force, vertical and horizontal force, and F_o, P_o, and S_{fv}. Sensors attached closer to the centre of mass appear more appropriate for measuring sprint performance (i.e. sprint times and velocity) and collecting force data. Sensors attached distally (i.e. closer to the foot), provide a more accurate detection of temporal step measurement variables. With the abrupt changes in body position during the initial start take-off, the in-between scapulae position (vest pouch) may be subjected to more movement for this phase of the sprint and thus less valid and reliable, though more research is needed into both positions. Sensor attachment which allows freedom of movement and minimises skin movement artefact are other important aspects requiring consideration. Straps and adhesive tapes were mainly used to attach the sensors to the segments of interest in the studies in this review. These methods are flexible and convenient to use, however, errors caused by skin movement may be considerable. Sensors placed in-between the scapulae may result in extra external noise when housed in a vest due to the sensor movement and possible impacts onto the body, and therefore maybe better placed on the skin for greater accuracy. Another important note related to sensor attachment was to ensure the axes of the wearable sensors align with the anatomical axes of the segments. After sensor attachment, static and dynamic calibration procedures need to be performed to obtain segment calibration. Moreover, the accuracy of the orientation estimation can be affected by calibration stages of the individual sensors (i.e. accelerometer, gyroscope, and magnetometer), biases, diverse noise types, and sensor fusion algorithm issues. Using higher sampling rates (>200 Hz) improves agreement levels when measuring sprint performance, temporal, displacement and force measures. Practitioners should consider higher end sampling rates (500-1000 Hz) to improve precision and accuracy during data collection. This is improving with increasing capabilities of technology. Synchronisation of sensors and references systems should be performed with an electronic trigger, rather than observational technique, which could lead to differences between measurement methods. Information on filtering frequencies was minimal, therefore, future research is needed on data logging and data processing methodologies.

Future research is required to completely assess validity and reliability measurements from wearable sensors during sprint-running. Specifically, the validity and reliability of short distance sprint split times (< 20 m), and the inter-day reliability of additional variables of interest. As average and peak velocity was found to show mixed validity from different methodologies, further research is required to ascertain whether wearable sensors can accurately measure these variables. As mixed results have been found in measures of every 10 m during a sprint, future studies may wish to investigate the analysis of multiple step contacts, rather than a single step contacts and arbitrary distance windows for the assessment of kinetic and kinematic data. Step analysis can be split into various groupings such as groups of every 4 steps (99, 101), or initial 2 steps for the start and steps 3-10 for initial acceleration (79). Moreover, future research is required to fully understand the intra and interday reliability of all variables of interest from wearable sensors.

3.5 Conclusions

Wearable inertial sensors enable the collection of kinematic and kinetic data during sprinting in a simple and time efficient manner outside of a laboratory setting. A wide range of validity and reliability measures were used and compared to different referenced systems with the accuracy of measurements seemingly affected by methodological differences. In summary, caution is warranted for findings related to the start and initial acceleration phase of sprint-running, as reduced validity and reliability was found during variables measured < 20 m. This is most likely due to the movement of the lower back in relation to the centre of mass as the sprinting posture becomes more upright. Sensors attached to a more distal placement (i.e. closer to the foot), provide a more accurate detection of temporal step measurement variables, though sensors attached on the lower back appear suitable for measuring sprint performance (i.e. sprint times and velocity) and force data. Using a higher the sample rate (> 200 Hz) improves accuracy levels in sprint times and velocity, temporal, displacement and force measures. The attachment method used to fix a sensor to the body requires consideration in sprinting studies as the high-speed movements of the trunk and limbs means that an appropriate attachment method could minimise skin and clothing artefact movements. Moreover, the attachment method and calibration method can impact on potential errors caused by improper alignment to anatomical axes. Though the validity and reliability of wearable inertial sensors appears promising, due to the small number of studies in this area, and differences in methodologies, additional research is needed to verify the findings of this review.

Section 2. Quantifying Mechanical Rotational Kinematic Variables from Inertial Measurement Units During Sprint-Running.

Chapter 4. Can Inertial Measurement Units Quantify Thigh Rotational Kinematics During Sprint-Running?

In this section, IMUs were used to quantify thigh rotational kinematics during sprint running. The concurrent validity from IMU measurements of sagittal plane rotational kinematics (displacement and velocity) of the thigh were compared with current gold standard reference system of motion capture. Moreover, using test-retest experimental procedures this section also analysed the reliability of IMU's on sagittal plane rotational kinematic variables during over ground sprint-running.

Chapter 4. Can Inertial Measurement Units Quantify Thigh Rotational Kinematics During Sprint-Running?

This chapter comprises the following paper currently in review in the Journal of Measurement in Physical Education and Exercise Science.

Reference: Macadam, P., Cronin, J., Uthoff, A., Nagahara, R., Tinwala, F., Graham, S., Diewald, S., Neville, J. Can inertial measurement units quantify thigh rotational kinematics during sprint running? *Measurement in Physical Education and Exercise Science.*

Author contributions: Macadam P, 80%, Cronin J, 6%, Uthoff A, 3%, Nagahara R, 3%, Tinwala F, 2%, Graham S, 2%, Diewald S, 2%, Neville J, 2%

4.0 Prelude

From Chapter 3 it was established that due to a wide range of methodological differences, a clear understanding of the validity and reliability of different inertial sensors in quantifying sprint performance has yet to be established. In addition, the use of inertial sensors to quantify rotational kinematics during sprinting had not been investigated. Accurately capturing and analysing kinematic data (joint angles, velocities, and accelerations) is of importance to practitioners as the information can provide a great deal of insight into sprint-running performance and irregularities. Though motion capture system is considered the current gold standard reference system for motion analysis, this system is not without limitations. For example, the system is not portable, expensive to purchase, has a limited capture volume and requires a trained technician to analyse the data. Fundamental understanding of sprint-running mechanics is often fairly linear in quantification, i.e. split times, distance travelled, high speed metres, etc. The importance of quantifying rotational movement would seem important especially with the emergence of new WR technology to load the lower limbs whilst sprint-running. The purpose of this chapter was to investigate the capability of an IMU for quantifying sagittal plane rotational kinematics of the thigh during 50 m sprint-running. Therefore, test-retest reliability of the capability of an IMU in providing rotational kinematics (thigh angular displacement and velocity) and the validity comparison of these variables to motion capture was assessed.

4.1 Introduction

The popularity of running and sprint-running in recreational settings, sport training and competitive games has encouraged a considerable body of research (73, 99, 114). This has been potentiated by advances in technology including increased frame rates in cameras, wearable sensors, force plates and improved motion capture analysis and computer modelling systems. Accurately capturing and analysing kinematic data (joint angles, velocities, and accelerations) is of importance to practitioners as the information is able to provide a great deal of insight into locomotion performance and irregularities (96, 146). Though three-dimensional motion capture system is considered the current gold standard reference system for motion analysis, this system is not without limitations (92, 147). For example, the system is not easily portable, expensive to purchase, has a limited capture volume and requires a trained technician to collect the data. Therefore, wearable sensors have been put forward to address most of the aforementioned limitations (69).

Wearable sensors, such as an IMU can measure linear and angular motions in three-dimensional space without relying on external reference systems that require setup and have limited capture volume, such as motion capture or video systems. IMUs are capable of obtaining the position and orientation of a rigid segment using an array of onboard sensors, usually comprised of a 3-axis accelerometer, 3-axis gyroscope, and a 3-axis digital magnetometer, or a combination (49). Accelerometers measure acceleration and tilt, gyroscopes measure angular velocity, and magnetometers provide orientation information. Advances in microelectromechanical systems have enabled these light, low cost, and low power body-mounted sensors to be a more practical option than laboratory-based equipment. Raw data from IMUs can be combined with sensor fusion algorithms to provide unit orientations, which in turn can be used to derive reliable spatio-temporal parameters of locomotion (50). These capabilities enable IMUs to collect a large amount of data regarding translational and rotational kinematics.

The importance of rotational kinematics was noted by Dorn et al. (43), who found that faster running speeds (>7.0 m/s) involved higher step frequencies, which were mainly produced by greater angular velocities from the hip joint in the swing phase. Wiemann and Tidow (152) reported that a sprinter’s speed is directly related to the velocity of leg extension - a movement started from the highest point of the knee lift, down to foot contact and continued during the support phase. Furthermore, Ansari et al. (5) noted that hip, knee, ankle and shoulder joint rotational kinematics were important factors for sprinting technique and had a clear effect on sprint performance. Understanding and measuring the rotational kinematics from the legs during sprint-running may assist practitioners in monitoring a different form of training load compared to cumulative linear measures from force plates or from trunk mounted sensors.

Recently researchers have shown that sensors within vest harnesses have shown poor reliability and validity (mean change 41-160%, CV 14-33%) for quantifying peak vertical acceleration of the body and vertical ground reaction forces, compared to gold standard reference systems, most likely due to the whipping movements between the vest and the body that appear to cause extraneous peak accelerations (46, 103). Therefore, affixing an IMU to the thigh via adjustable elastic straps would enable more direct measures of leg movement and may mitigate the issues associate with vest placement.

Previous studies with wearable sensors attached to the thigh have quantified rotational kinematics during treadmill and over ground running (108, 116, 141, 153) and over ground sprinting (142, 143). The wearable sensors were able to detect greater hip joint range of motion at sprinting speeds (142) compared to running speeds (116, 142). However, only Nuesch et al. (108) has reported validity measures of rotational kinematics from an IMU compared to motion capture system. From findings collected at treadmill running speeds (~ 3.0 m/s), IMU measures from the hip joint were found to underestimate range of motion (4-9^{o}) with a coefficient of multiple correlation of 0.54 reported (108). Nuesch et al. (108) advised that differences between systems may be due to variances in the positioning of sensors and markers, and soft tissue movement, thus segment positions and different definitions of joint axes may have occurred between systems. A review into IMUs during running suggests that placement of sensors closest to the segment of interest along with the use of bi/tri- axial accelerometers appear to provide the most accurate results (105). However, application of IMU usage is still underutilised in research, possibly due to the lack of standards for sensor placements and distinct joint coordinate systems, which limits the correct joint kinematic calculations (148). Furthermore, differences between the placement of the sensor, type of sensor, running surface and running speeds have resulted in mixed validity findings when other kinematic and kinetic variables were compared to referenced systems (14, 70, 141).

During sprint training, athletes seek to improve the biomechanics of their actions in order to produce optimal technique in competition. Assessing biomechanics during training currently requires technologies with recognised limitations. IMUs may provide an objective measurement technology capable of circumventing these limitations, but further research is needed to validate the utility of wearable sensors with the current gold standard reference systems. Therefore, the purpose of this study was to investigate the capability of an IMU in providing accurate rotational kinematics (thigh angular displacement and velocity) during 50 m sprint-running performance compared to motion capture system. It was hypothesised that the IMU would provide reliable and valid measures of rotational kinematics during over ground sprint-running.

4.2 Materials and Methods

4.2.1 Subjects

Fourteen male participants (21.4 ± 2.5 years; 174 ± 4.8 cm; 67.1 ± 5.8 kg; 9.2 ± 2.5 training years; 11.4 ± 0.5 s 100 m personal best time) from university athletic clubs were recruited. Written informed consent was obtained from the participants prior to their participation and they were advised that could withdraw from the study at any time without repercussion. The Institutional Ethics Committee of Auckland University of Technology provided approval for this study.

4.2.2 Inertial Measurement Unit

An IMU (IMeasureU Limited, Auckland, New Zealand) consisting of a ±16g 3-axis accelerometer, ±2000°/s 3-axis gyroscope, and a ±1200μT 3-axis magnetometer was used to collect rotational kinematics from the left thigh. The accelerometer was calibrated using gravity vectors recorded in each of the primary orientations, and the gyroscope was factory calibrated. The same type of IMU was attached to the shank to enable synchronisation between systems. This IMU was attached to the medial border, approximately the mid-point, of the left shank and was used only for synchronisation between systems. The shank IMU is closest to the ground, and thus was used for synchronisation as it provides the clearest ground impact signal with minimal force absorption through the joints. Data were logged to the onboard memory of the IMU at 500 Hz for the duration of the trials, and then downloaded after each session for processing. The IMU was attached to the middle and lateral surface of the thigh, corresponding to the mid-point between the greater trochanter and lateral epicondyle of the femur, using elastic straps with tape placed onto the strap and leg to minimise movement (Figure 9).

Figure 9. Marker set-up and inertial measurement unit attached to the mid-point of the thigh and shank of the left leg.

4.2.3 Motion Capture System

Motion capture systems (Raptor-E and Eagle, Motion Analysis Corporation, Santa Rosa, CA, USA, sampled at 250 Hz) were placed to create two capture volumes, 0-9 m (21 cameras) and 41-50 m (16 cameras) sections. All cameras connected to a single computer to capture three-dimensional coordinates of retroreflective markers affixed to the participant's body. During static and dynamic calibration, each participant had 46 markers attached (24 single markers attached to anatomical landmarks, 22 in fixed clusters) (Figure 9). Sixteen markers (8 single, 8 cluster) were removed post calibration.

4.2.4 Data Capture

Following warm-up, participants wearing spiked shoes performed three sub maximum sprints (50, 75 and 90%) and two maximum effort sprints over 50 m from a block start position. A period of familiarisation with the starting blocks was permitted. At the start of each trial, participants performed a pogo jump to synchronise the IMU and motion capture systems. Two motion capture systems were sampled alongside a 1000 Hz force plate system built into the running track which was connected to a single computer (TF-90100, TF-3055, TF-32120, Tec Gihan, Uji, Japan) to detect GRF. Synchronisation of the IMU and the motion capture system was facilitated using the force plate system which was used to detect foot strike and toe-off from the pogo jump performed prior to each trial. In order to appropriately detect the foot strike and toe-off instants eliminating the influence of random noise, GRF signals were filtered using a 4th order Butterworth low-pass digital filter with a cut-off frequency of 50 Hz (99, 101). Foot strike and toe-off instants were identified using a vertical GRF threshold set at 20 N.

4.2.5 Data Analysis

Following block clearance, data from the first three left leg steps were obtained during the initial acceleration phase (0-9 m), and one step from the left leg was collected during the maximum velocity phase (41-50 m). Due to the participant's speeds during the maximum velocity phase, only one step from the left leg was captured in this phase. The motion capture data was imported into Vicon Nexus 2.7 (Vicon, Oxford, UK) and reconstructed to determine marker locations in three-dimensional space. Each trial was manually inspected for gaps and/or labelling errors. A 4th order Butterworth low-pass digital filter with cut-off frequencies based on residual analysis was used for smoothing the motion capture data (97). Dynamic calibration was used to determine the functional hip and knee joint centres using the SCoRE / SARA pipeline in Vicon Nexus 2.7 (47). Kinematic variables of interest were modelled using the functionally defined joint information and a customised variation of the lower limb model (16). The variables of interest were thigh segment kinematics (position and orientation), angular displacement and angular velocity.

Acceleration and rotational velocity data were identified from the IMU and imported into Matlab (V2019b, Mathworks, Natick, Massachusetts, USA). Orientation of each sensor was calculated using a sensor-fusion algorithm; in which angular velocity and acceleration data were combined to minimise the effects of gyroscope drift and accelerometer noise. An in-built complementary filter in Matlab 2019b was used to obtain orientation of the sensor, using ZYX frame-rotation Euler angles. The recorded waveforms from the IMU for kinematics of the thigh were separated by steps by identifying the maximum flexion and extension (thigh range of motion) in the Z-axis, corresponding to the sagittal plane. Only a local reference frame was needed for the analysis, therefore the magnetometer data was not utilised. Cross-over movement from other planes was assumed to be minimal.

4.2.6 Statistical Analysis

Means and SD were calculated to represent the centrality and spread of rotational kinematic data. Test-retest reliability of two trials from eleven steps was established via three separate statistical methods: 1) the change in mean (CM) was reported as a percentage fluctuation in mean to establish if average performance increased or decreased across the data collection trials, 2) CV was reported to determine typical error as a percentage of each participants mean, and, 3) ICC with 95% confidence intervals (CI) were reported to indicate the consistency of an athletes score in relation to their ranking in the group. The CV was calculated from (SD/ Mean) * 100. The current investigation set reliability thresholds of CV $\leq$ 10% (6), ICC $\geq$ 0.70 (83).

Concurrent validity of the IMU was investigated relative to the mocap data values using relative error, Bland-Altman bias (mean error) and 95% LoA, and ICCs with 95% CI. The first three left leg steps during the initial acceleration phase, and one step from the left leg from the maximum velocity phase were compared between systems for validity. The relative error for each variable was computed from: (mean IMU – mean motion capture/mean motion capture) x 100 (132, 133). Bland-Altman plots were used to visualise systematic differences. The systematic bias represents the absolute difference between the measurement systems, and the random errors are calculated by the SD of the difference between the IMU and motion capture system, and then multiplied by 1.96. Together they form the 95% LoA (17). ICC was interpreted as follows: moderate (0.50–0.69), high (0.70–0.89), and excellent (0.90 and above) (11). The mean data from two sprint trials from IMU and motion capture system was analysed for the concurrent validity assessment.

4.3 Results

The IMU derived thigh angular displacement over the 50 m sprints were 96.4^{o} and 97. 3^{o} for trials one and two respectively, resulting in high levels of reliability (CM 1%, CV 6.7%, ICC 0.95). Results for angular velocity were also found to be reproducible between the two trials with flexion values of 768 ^{o}/s and 756 ^{o}/s, and extension 688 ^{o}/s and 681 ^{o}/s, respectively (CM 1.2-1.5%, CV 8.9-9.7%, ICC: 0.95-0.96) (Table 12).

Compared with the motion capture system measures, the IMU was found to underestimate thigh angular displacement during the initial acceleration phase (relative error -6.7%, ICC 0.79), and during the maximum velocity phase (relative error -9.0%, ICC 0.84) (Table 13). The Bland–Altman bias (acceleration: 7.5^{o}, maximum velocity: 10.4^{o}) and LoA (acceleration: -5.5, 20.5^{o}, maximum velocity: 3.5, 18.2^{o}) are presented in Table 13 as well as Bland–Altman plots in Figure 10.

Measures of thigh angular velocity from the IMU were found to be underestimated compared to the motion capture system during the initial acceleration phase (flexion: relative error -5.3%, ICC 0.54 and extension: relative error -6.2%, ICC 0.64) (Table 14). Similarly, during the maximum velocity phase, measures of thigh angular velocity from the IMU were found to be underestimated (flexion: relative error -12.3%, ICC 0.53, extension: relative error -16.4%, ICC 0.45) compared to the motion capture system (Table 14). The Bland–Altman bias (acceleration: 38.7$^{o}\cdot s^{-1}$ flexion, 35.7$\cdot s^{-1}$ extension, maximum velocity: 114$^{o}\cdot s^{-1}$ flexion, 146$^{o}\cdot s^{-1}$ extension) and LoA (acceleration: -142, 220$^{o}\cdot s^{-1}$ flexion, -186, 257$^{o}\cdot s^{-1}$ extension, maximum velocity: 76.2, 306 $^{o}\cdot s^{-1}$ flexion, -18.3, 312$^{o}\cdot s^{-1}$ extension) are given in Table 14 as well as Bland–Altman plots in Figure 11.

Table 12. Reliability results from the inertial measurement unit of thigh angular displacement and velocity from all ten left leg steps during 50 m sprint-running.

Measurement	Trial 1	Trial 2	Change in the mean (%)	Coefficient of variation (%)	Intraclass correlation (90% CI)
Angular displacement (^{o})	96.4 ± 6.52	97.3 ± 6.91	1.0	6.7	0.95 (0.89-0.98)
Flexion angular velocity ($^{o/}$s)	768 ± 81.2	756 ± 85.5	1.5	9.7	0.96 (0.91-0.99)
Extension angular velocity ($^{o/}$s)	688 ± 65.4	681 ± 60.3	1.2	8.9	0.95 (0.87-0.98)

CI = confidence interval

Table 13. Relative error, Bland-Altman bias and 95% limits of agreement (LoA) and Intraclass correlation between the inertial measurement unit and motion capture system of thigh angular displacement.

Sprint phase	Inertial measurement unit (^{o})	Motion capture (^{o})	Relative error (%)	Bias (^{o})	LoA (^{o})	Intraclass correlation (90% CI)
Initial acceleration	93.3 ± 9.0	100 ± 11.7	6.7	7.5	-5.5, 20.5	0.79 (0.62-0.90)
Maximum velocity	101 ± 6.4	111 ± 8.2	9.0	10.4	3.5, 18.2	0.84 (0.66-0.93)

Initial acceleration = three initial steps from left leg, Maximum velocity = one step, CI = confidence interval

Table 14. Relative error, Bland-Altman bias and 95% limits of agreement (LoA) and Intraclass correlation between the inertial measurement unit and motion capture system of thigh angular velocity.

Sprint phase	Inertial measurement unit ($^{o}/s$)	Motion capture ($^{o}/s$)	Relative error (%)	Bias ($^{o}/s$)	LoA ($^{o}/s$)	Intraclass correlation (90% CI)
Initial acceleration Flexion	691 ± 103	730 ± 97.3	5.3	38.7	-142, 220	0.54 (0.14-0.73)
Extension	573 ± 108	611 ± 102	6.2	35.7	-186, 257	0.64 (0.32-0.79)
Maximum velocity Flexion	814 ± 89.0	929 ± 99.4	12.3	114	-76.2, 306	0.53 (0.09-0.78)
Extension	749 ± 54.1	896 ± 71.9	16.4	146	-18.3, 312	0.50 (0.07-0.73)

Initial acceleration = three initial steps from left leg, Maximum velocity = one step. CI = confidence interval

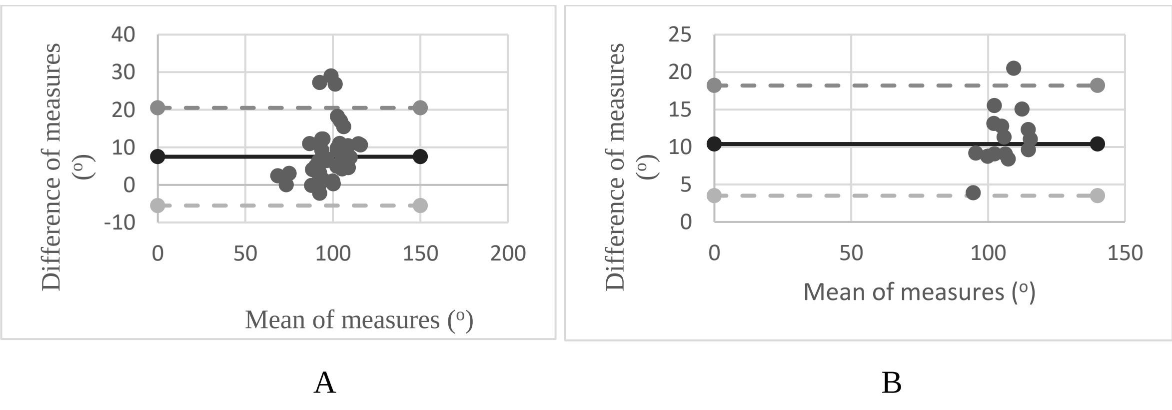
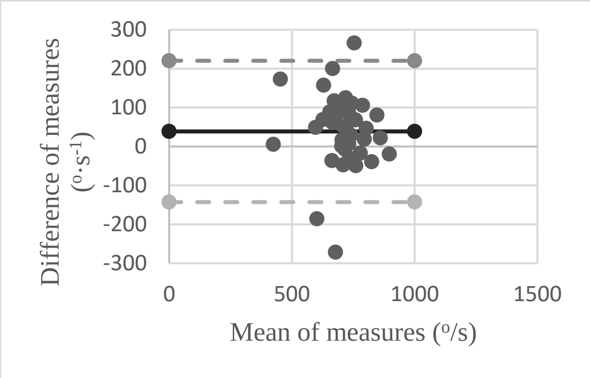
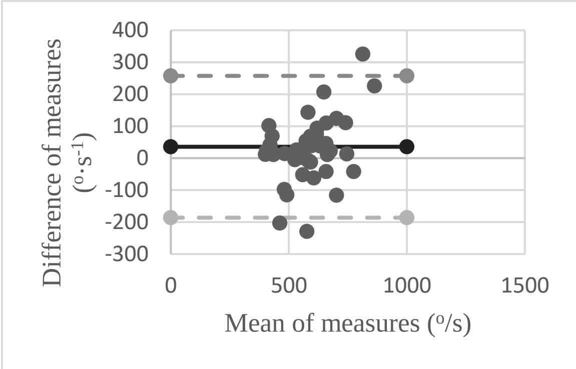


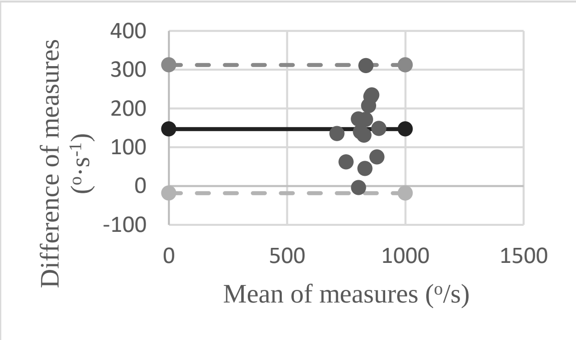
Figure 10. Bland–Altman plot comparing the IMU and motion capture system estimates of angular displacement during initial acceleration (A) and maximum velocity (B). Bias: thick solid black line, 95% limits of agreement: dashed.



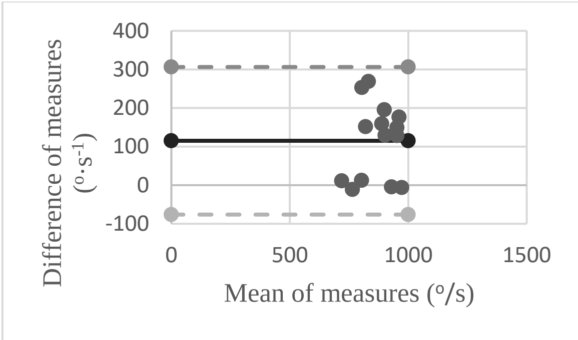
A Flexion



B Extension



C Flexion



D Extension

Figure 11. Bland–Altman plot comparing the IMU and motion capture system estimates of angular displacement during initial acceleration (A) and maximum velocity (B). Bias: thick solid black line, 95% limits of agreement: dashed.

4.4 Discussion

The purpose of this study was to investigate the capability of an IMU in providing reliable and valid sagittal plane rotational kinematics during acceleration and maximum velocity phases of over ground sprint-running compared to motion capture system. The main findings were: 1) IMU derived measures of thigh angular displacement and velocity were found to be reliable (change in the mean 1-1.5%, CV 6.7-9.7%, ICC: 0.95-0.96), and 2) the IMU underestimated thigh angular displacement (relative error -6.7 to -9.0%, Bland-Altman bias 7.5-10.4º, ICC 0.79-0.84) and thigh angular velocity (relative error -5.3 to -16.4%, Bland-Altman bias 38.7-146 º/s, ICC 0.45-0.64) with greater discrepancies found during the maximum velocity phase. This research provides some of the first insights into the reliability and validity of measuring sagittal plane rotational kinematics during over ground maximum velocity sprint-running.

This study demonstrates that IMUs may be reliable for measuring rotational kinematics during over ground sprinting (CM <2%, CV <10%, and ICC ≥ 0.95). This research not only conforms with existing research findings i.e. during walking and running, IMU derived sagittal plane hip, knee and ankle rotational kinematics were also found to be reliable (ICC 0.94–0.99, coefficient of multiple correlation 0.95-0.99, and root mean square error of waveforms 3-7°) (108, 145), but builds upon that body of research by being the first to test the utility of this technology to describe motion at higher sprint velocities.

During the initial 9 m of acceleration, the IMU was found to underestimate the angular displacement of the thigh with average values of 93.3° compared to 100° identified by the motion capture system. Despite these differences, a high level of correlation between the two measurements systems was found (ICC = 0.79) with a relative error of 6.7%. Comparable, though smaller values of sagittal angular displacement (89.1-90.6°) were found in a study that investigated sprint performance (15-25 m) of team sport participants using inertial sensors sampling at 200 Hz (142). Differences between these findings may relate to different phases of the sprint being measured, types of sensors used, lower sampling rate, and sprinting ability of the participants used. Moreover, the accuracy of the orientation estimation can be affected by calibration stages of the individual sensors (i.e. accelerometer and gyroscope), and diverse noise types (148). From the maximum velocity phase in this study it was observed that the IMU underestimated angular displacement, (101° compared to 111°), though a high correlation was found between systems (r = 0.84) with a typical error of 9.0% noted. Though high levels of correlation were identified between the systems during the acceleration and maximum velocity phases of the sprint, it appears that the maximum velocity phase is associated with greater discrepancies than the acceleration phase compared to the reference system (relative error: 6.7% versus 9.0%, Bland-Altman bias was 7.5° versus 10.4°, respectively).

Regarding angular velocity, a moderate correlation (ICC = 0.54-0.64) was found between measurements during the initial acceleration phase. Flexion and extension actions during the initial acceleration phase were underestimated by the IMU compared to motion capture with a typical error of ~5-6% found. During the maximum velocity phase, the correlation between systems was moderate (ICC = 0.50-0.54), while the typical error between systems increased to ~12-16%. Similarly to angular displacement findings, measures of angular velocity were found to be comparable (650.5-662.4 °/s) to the study of Struzik et al. (142) as compared to the acceleration phase findings (565-682 °/s) of this study. Differences between sprint phases within this study are highlighted in larger typical error and bias measurements during the maximum velocity phase, though a smaller LOA was found during this phase.

The strength of association between displacement and velocity measurements was less, and typical error and bias were greater with the maximal velocity phase of sprinting. At the start of accelerated sprint-running a sprinters body position changes out of a crouched block start to a more upright position where the range of motion and velocity of the thigh increase with each step

(143). During maximum velocity sprinting, the body is more upright, and the limbs experience greater displacement and velocity as higher sprinting velocities are attained (96, 142). It is likely these factors contributed to the lower correlation and increased typical error values found during the maximum velocity phase compared to the acceleration phase. In addition, as only one step was captured and compared to the motion capture system from the maximum velocity phase, differences in sprint phase findings may be affected by this limitation.

The reader needs to be cognisant of several limitations when interpreting the findings of this article. Findings of this study only apply to maximal effort 50 m straight line sprint-running undertaken in a non-fatigued state. As only one step was recorded during the maximum velocity phase, additional research is required to clarify the findings at maximum velocity speeds and over a greater number of steps. We contend however, that if we averaged a number of steps the alignment between motion capture and IMU measures would have been closer. Furthermore, IMUs are analysed in a local reference frame only, rather than being calibrated to the global reference frame, and thus the true (sagittal plane). This places more emphasis and potential error on the placement of the IMU on the thigh. Although most of the movement will occur in the sagittal plane (if placed correctly), there will still be some movement in other planes that is not being accounted for, but it was assumed to be minimal. Moreover, the dominant acceleration when wearing a hip attached sensor is in the flexion-extension direction of movement, and movement in this plane represents the best single-axis indicator for predicting energy expenditure (149). Finally, the complimentary filter used may be more accurate if magnetometer data was utilised. For example, an attitude and heading reference system algorithm uses a magnetometer and is able to remove the magnetic distortion; however, we chose not to use this method as though they work well in outdoor spaces, they do not work well in indoor spaces due to varying arrangements of magnetic materials (155). As the testing environment was an indoor sports hall with metal beams, equipment, etc. the additional noise was thought a confounding variable that would affect the accuracy of the data.

4.5 Conclusions

The findings from this study showed that sagittal plane thigh rotational kinematics can be reliably collected from a thigh mounted IMU. Though results indicate that the IMU values are highly correlated to motion capture system values, bias towards underestimating rotational kinematics was found, with greater errors occurring during the maximum velocity phase. This may have occurred due to the greater limb velocities and the fewer steps collected in the maximum velocity phase. The ability to track and monitor thigh kinematics enables practitioners to assess the individual contribution of the lower limbs during sprint-running. Moreover, as sensors attached to the trunk that measure centre of mass are often based on accelerations which are subject to noise from soft tissue and clothing artefact, angular rotations of limbs can be more robust to these spikes in noise and provide a more direct measure of work. Though this approach is not without limitations, the findings suggest it has the potential to be successfully deployed as a technique for measuring rotational movement during sprint-running in the field at a fraction of the cost of existing laboratory-based systems. Furthermore, it is likely that the correlations would be stronger and variability and bias less, with a greater number of steps collected. However, such a contention needs investigation.

Section 3. Effects of Thigh Wearable Resistance on Kinematic and Kinetic Variables During Sprint-Running

Chapter 5. Load Effects of Thigh Wearable Resistance on Angular and Linear Kinematics and Kinetics During Non-Motorised Treadmill Sprint-Running

Chapter 6. Changes in Step Kinematics and Kinetics During Over Ground Sprint-Running with Thigh Wearable Resistance

Chapter 7. Rotational Mechanical Workload Responses During Over Ground Sprint-Running with Thigh Wearable Resistance

Chapter 8. The Effects of Thigh Positioned Wearable Resistance on 40 m Sprint Performance: A Longitudinal Single Case Design Study

Acute cross-sectional descriptive studies investigated the effects of thigh WR on the kinetics, linear and rotational kinematics, and rotational work of the lower limbs determined from non-motorised treadmill and over ground sprint-running maximum sprint-running. A single subject design study examined changes in sprint performance and rotational kinematic responses in one male sprinter following a lower-limb WR training period of 5 week.

Chapter 5. Load Effects of Thigh Wearable Resistance on Angular and Linear Kinematics and Kinetics During Non-Motorised Treadmill Sprint-Running

This chapter comprises the following paper published in the European Journal of Sport Science.

Reference: Macadam, P., Nuell, S., Cronin, J., Diewald, S., Forster, J., Fosch, J. Load effects of thigh wearable resistance on angular and linear kinematics and kinetics during non-motorised treadmill sprint-running. *European Journal of Sport Science.* doi: 10.1080/17461391.2020.1764629

Author contributions: Macadam P, 85%, Nuell, S. 4%, Cronin J, 4%, Diewald S, 3%, Forster, J, 2%, Fosch, J. 2%

5.0 Prelude

From the review of the literature in Chapter 2, it was determined that a wide array of placements and magnitudes of WR have been used during sprint-running research. One of the challenges to the users of WR is understanding the effects of the myriad of loading options that this form of technology provides. For example, loads can be affixed to the trunk, arms, thighs and calves and these loads can be varied from proximal to distal, anterior to posterior, and medial to lateral. Furthermore, different loads, usually represented as a percentage of BM can be used. Of interest in this thesis is the effect of different thigh loads on sprint kinematics and kinetics. From the critique of the literature it was identified that limited research had investigated the effects of leg loading under 3% BM, and that distal placed loading had not been used in sprint-running. From Chapter 4, measures of rotational kinematics were able to be quantified from thigh attached IMUs, thus providing an additional method to measure the effects of thigh WR on rotational kinematics. This chapter aimed to understand the acute effects of three different loading magnitudes (1, 2, 3 % BM) attached distally on the thighs during maximum effort non-motorised treadmill sprint-running.

5.1 Introduction

There are multiple training options available to produce speed adaptation; however, this adaptation needs to be specific to the requirements of the athlete and the sport (8, 41). WR is one form of training option available to practitioners that allows this specificity by enabling loads to be directly attached to different parts of the body (73, 74). Therefore, WR has the potential to address some limiters to transferences to performance that other training options lack (e.g. velocity, range of motion, contraction type, metabolic specificity to the activity of interest, and disconnected from the training and/or competition environment) (41). One of the challenges to the users of WR however, is understanding the effects of the myriad of loading options that this form of technology provides. For example, loads can be affixed to the trunk, arms, thighs and calves (73, 74) and these loads can be varied from proximal to distal, anterior to posterior, and medial to lateral. Furthermore, different loads, usually represented as a percentage of BM can be used. Of interest to these authors is the effect of different thigh loads on sprint kinematics and kinetics.

Previously from over ground sprints with WR ranging 2.4% to 5% BM attached to the whole leg step frequency was significantly decreased (-1.3% to -3.6%), though step length was minimally changed (-0.6% to 0.8%, $p > 0.05$) (13, 77, 136). Similarly, during NMT sprinting with whole leg placement WR, loads of 5% BM were found to significantly overload peak velocity (~-2% to ~-5%) and step frequency (~-4%) while having minimal impact on step length (134). Furthermore, WR attached to the legs provided a significant overload to contact time (4.3-4.7%) resulting in the athlete having to produce a greater amount of vertical force (4-4.5%) to overcome the additional loading (134). During sub-maximum running on a motorised treadmill, whole leg attached WR of 1, 3 or 5% BM did not significantly change any linear step kinematic variables, though significant increases were found in horizontal (4-7%) and vertical (1-2%) forces and impulses (30).

Previous WR loads have been placed evenly on the legs, therefore, practitioners may be interested in understanding the effect of placing the WR more distal to the hip joint (i.e. distal aspect of the thigh) which increases the rotational inertia associated with moving and controlling the thigh (74). Though no previous sprinting studies have assessed changes in thigh WR, two studies (80, 81) investigated the effects of mid to upper thigh loading during 10-minute motorised treadmill running at 3.3 m/s. Thigh loads 0.6% and 1.4% BM resulted in significantly increased VO_2 of 1.7% and 3.5%, respectively; however, the loads did not significantly change any linear kinematic variables of interest (stride length: 0-0.3%, contact time: 0-0.4% and flight time -1.1% to 3.2%) (80). Given the previously more proximal placement (WR was placed mid to upper thigh), kinematic results may be different with a more distal placement (i.e. increased rotational inertia). Moreover, no rotational kinematic or kinetic measures were reported from the studies limiting further understanding of thigh WR effects.

Though NMT and over ground sprinting do not result in the same outputs since the task constraints change with the demand to overcome the friction of the treadmill, the focus of this paper is on the effects of WR during NMT sprint-running. NMTs are becoming increasingly popular as a tool for training, and laboratory-based research. Compared to a motorised treadmill, where belt speed is controlled by an external motor, NMTs are participant driven and provide a closer experience to over ground locomotion by allowing rapid acceleration and deceleration, step-to-step gait variability and internal pacing (37, 140). Therefore, NMTs provide an attractive alternative to training as they allow a closer approximation of over ground sprinting and running in terms of pacing and gait (45). A limitation of the NMT is it quantifies linear kinematics and kinetics; however, WR provides a rotational overload and so other technology, such as an inertial measurement unit (IMU), is required to understand the rotational effects of WR.

Though several studies have examined the linear kinematic and kinetic effects of different magnitudes of WR on sprint performance during sprinting, the effects of incremental loading remain unclear. Moreover, only 5% BM has been investigated during sprinting on a non-motorised treadmill. In addition, the effects of the distally placed WR have yet to be examined. Given the inertial changes of the limb with WR loading, it is important to understand how this loading may change sprint-running rotational movement mechanics prior to further investigating its use as a training tool. Therefore, the aim of this study was to investigate the load effects of WR attached distally to the thighs on kinematics and kinetics during maximum sprint-running.

5.2 Methods

5.2.1 Experimental Design

A cross-sectional design was used to investigate the effects of WR on linear and angular kinematics and linear kinetics during maximum effort sprint-running. All subjects performed a maximum effort 10-second sprint on an NMT with a thigh attached IMU, and with and without WR of 1, 2, and 3% BM in a randomised manner.

5.2.2 Subjects

Fourteen recreational active healthy male and female subjects volunteered to take part in this study (24.9 ± 4.2 years, 68.4 ± 7.1 kg, 172.1 ± 6.8 cm). All subjects provided written informed consent before participating and completed a health questionnaire to ensure that they were fit for testing. The Institutional Ethics Committee of Auckland University of Technology provided approval for this study.

5.2.3 Equipment

A Woodway Force 3.0 (Eugene, OR, USA) NMT ergometer was used to quantify the sprint kinetics and kinematics. The NMT system used in this study featured a user-driven vulcanized rubber belt, the mechanics of which feature 12 guiding rollers and 114 ball bearings. The subjects were harnessed round the waist to a vertical strut at the rear of the system. A nonelastic tether secured the harness to a load cell and a locking vertical-sliding gauge allowed the collection of horizontal force data. This sliding gauge was manually adjustable (and securable) to each subject's hip height to enable horizontal alignment of the tether to the load cell during running trials. Calibration of the load cell took place before the testing session by hanging a selection of known weights from the tether as instructed by the manufacturer. Vertical force output was collected using 4 load cells positioned beneath the NMT belt. The velocity of the treadmill belt was collected by 2 optical speed microsensors located at the rear of the treadmill belt. Power output was measured by the NMT as the product of the force exerted on the horizontal load cell and the velocity of the treadmill belt. All variables were collected at a sampling rate of 200 Hz, using a hardwired system interface (XPV7 PCB; Fitness Technology, Adelaide, Australia). Methods similar to previous research (21, 36) were used to calculate step velocity, step frequency, step length, contact time, flight time, peak horizontal force, peak vertical force, and power output. Step kinematics were calculated from defining toe off and heel on position using a 100 N threshold from the vertical force data, which was filtered with a 40 Hz low pass 4th order Butterworth filter. To identify foot contacts from each leg, center of pressure from medial-lateral data was used to identify left or right leg.

An IMU (IMeasureU Limited, Auckland) consisting of a 3-axis accelerometer, 3-axis gyroscope, and a 3-axis magnetometer was used to collect rotational kinematics from the left leg. Data were logged to the onboard memory of the IMU at 500 Hz for the duration of the trials, and then downloaded after each session for processing. The accelerometer was calibrated using gravity vectors recorded in each of the primary orientations, and the gyroscope was factory calibrated. The IMU was attached to the middle and lateral surface of the thigh, corresponding to the mid-point between the greater trochanter and lateral epicondyle of the femur, using elastic straps with tape placed onto the strap and leg to minimise movement. Acceleration and rotational velocity data were identified from the IMU and imported into Matlab (V2019b, Mathworks, Natick, Massachusetts, USA). Orientation of each sensor was calculated using a sensor-fusion algorithm; in which angular velocity and acceleration data were combined to minimize the effects of gyroscope drift and accelerometer noise. An in-built complementary filter in Matlab 2019b was used to obtain orientation of the sensor, using ZYX frame-rotation Euler angles. The recorded waveforms from the IMU for kinematics of the thigh were separated by steps by identifying the maximum flexion and extension (thigh range of motion) in the Z-axis, corresponding to the sagittal plane. Only a local reference frame was needed for the analysis, therefore the magnetometer data was not utilized. Cross-over movement from other planes was assumed to be minimal. Previous IMU sprint studies have found that rotational kinematics measures were valid with root mean square error measures in shank angular displacement (≤ 5%) and velocity (≤ 10%), and trunk angular displacement (≤ 5%) (14, 23), with reliability in trunk angular displacement (≤ 6%) also found (14).

Participants wore Lila™ Exogen™ compression shorts (Sportboleh Sdh Bhd, Kuala Lumpur, Malaysia) for the duration of the testing session. The Exogen™ exoskeleton shorts enables multiple loads (with Velcro backing) ranging from 0.05-0.2 kg to be attached in numerous configurations. The three WR conditions were 1, 2 and 3% BM, which were attached to the distal aspect of each thigh, therefore the WR was distally placed evenly around each thigh with 2/3 of the load attached predominately to the anterior and the remaining 1/3 posteriorly (Figure 12).

A B

Figure 12. Example of A (0.5% per leg, total 1% body mass) and B (1.5% per leg, total 3% body mass) wearable resistance attached around the distal aspect of the thighs.

5.2.4 Procedures

Participants attended three separate days for familiarisation, and testing sessions, separated by four days. Following familiarisation for the first session, participants were randomly assigned to complete two of the four conditions during the 2nd session (e.g. 2% and unloaded) and the remaining two conditions during the 3rd session (e.g. 1% and 3%). Close-fitting sports clothing and running shoes were worn throughout the sessions. First, the subjects' height, mass, and age were determined and recorded.

The subjects were then required to undergo a standardised warm-up and familiarisation without any WR. Initially, the subjects jogged unloaded on the treadmill for 2 minutes. During this time, the subjects were encouraged to vary their pace to familiarise themselves with the feeling of accelerating on the foreign running surface. Two build-up sprints of 60% and 80% of the subjects' expected maximum velocity were then performed based on the findings of previous NMT sprint studies (21, 36). This consisted of a 3 second submaximal acceleration to the determined velocity, holding that velocity for 5 seconds, and then decelerating. To conclude the warm-up protocol, a 10 second maximum sprint was performed. Between each section of the warm-up, subjects could rest for 60 seconds, followed by a 3–4 minute rest period preceding the first trial. The data collection consisted of 10 second maximal velocity sprints under the 4 conditions. Throughout each 10 second trial, subjects were given continuous verbal encouragement to promote maximal effort. Rest between trials was 4 minutes for each participant after each trial.

5.2.5 Data Analysis

Previous NMT sprint studies (35, 134) have compared findings from approximately 25 steps over acceleration and maximum velocity phases during 6 seconds sprints. During the 10 second sprint in this study, the smallest number of average steps for subjects was 40. From unloaded sprinting, peak velocity was on average attained around step 14, therefore, the initial steps 1-14 were used to represent the acceleration phase (AP); the subsequent sixteen steps (i.e. steps 11-26), representing the maximum velocity phase (MVP1) and steps 27-40 representing the maintenance of maximum velocity phase (MVP2). An average of all steps was also calculated for each variable from all conditions. During each of the step phases, step kinematic and kinetic variables from the NMT were analysed over all foot contacts (i.e. left and right legs) phases, with angular kinematics from the IMU analysed from the left leg only. Force values for unloaded sprinting were normalised to BM. Force values for the WR condition were normalised to system mass, this was calculated from participant's BM plus the additional % BM from the WR for each condition.

5.2.6 Statistical Analysis

Standard descriptive statistics (means and SD) were reported for all statistical comparisons. Normal distribution of the data was checked using the Sharpio–Wilk statistic. Data were compared using a repeat-measures analysis of variance (ANOVA) with Bonferroni post hoc comparisons used to determine statistical difference between kinematic and kinetic variables between WR conditions for each step phase. Statistical significance was set at an alpha level of $p < 0.05$. ES (reported using Cohen's d) and 90% CI were described as trivial (<0.2), small (0.21-0.5), moderate (0.51–0.79) and large (>0.8) (27). Cohen's d was determined by calculating the mean difference between groups, and then dividing the result by the pooled SD (27).

5.3 Results

As trivial to small ES changes ($p > 0.05$) were found in linear kinematics and kinetics with WR during each step phase, only the average results for these sprint properties are shown in Table 15. Significant large ES differences within step phases and average results were found in rotational kinematics and are presented in Table 16.

Trivial decreases were found in velocity with all WR loads (-0.9 to -2.4%, ES 0.07-0.17, $p > 0.05$) (Table 15). The WR conditions resulted in significantly decreased average step frequency (-2.0 to -3.0 %, ES 0.19-0.47, $p < 0.05$) with loads of ≥ 2% BM, whereas average step length was increased with all loads (1.9-2.8%, ES 0.19-0.30, $p > 0.05$). Trivial to small increases were found in for contact time (1.2-2.9%, ES 0.10-0.25, $p > 0.05$) with trivial increases flight time (2.6-5.0% ES 0.08-0.13, $p > 0.05$). Regarding kinetics, trivial to small increases were found in average vertical force with all loads (0.2-4.7% ES 0.06-0.41, $p > 0.05$). Trivial to small decreases were found in horizontal force with 1% and 3% BM (-3.1% to -3.6%, ES 0.19-0.21, $p > 0.05$), though trivial increases were found with 2% BM (0.3%, ES 0.02, $p > 0.05$). Similar for power, trivial decreases occurred with 1% and 3% BM (-1.2% to -3.2%, ES 0.05-0.24, $p > 0.05$), whereas trivial increases were found with 2% BM (0.5%, ES 0.02, $p >0.05$).

Though thigh angular displacement was statistically unchanged with all WR during the initial acceleration phase of the sprint, during the maximum velocity phases, loads ≥ 2% BM resulted in a significant decrease (-7.0% to -14.8%, ES 0.80-1.14, p 0.00-0.04) in thigh displacement (Table 16). Moreover, from averaged steps, loads of ≥ 2% BM resulted in significantly decreased thigh angular displacement (-7.0% to -10.3%, ES 0.88-1.10, p 0.00-0.03). Regarding thigh angular velocity, no statistically significant changes were found with WR of 1% BM. However, 2% BM WR resulted in a significant decrease in angular velocity during MVP2 with greater changes found in extension velocity (flexion -6.8%, ES 0.46, p 0.03, extension -14.4%, ES 0.90, p 0.01). WR of 3% significantly decreased MVP1 and MVP2 (flexion -10.2% to -12.4%, ES 1.05-1.09, p 0.02-0.04, extension -11.3% to -15.5%, ES 0.79-1.15, p 0.00-0.01). Moreover, average angular flexion velocity (-10.2%, ES 1.07, p 0.02) and extension velocity (-12.0%, ES 0.85, p 0.01) were significantly decreased with 3% BM WR.

Table 15. Average linear kinematic and kinetic variables for unloaded and wearable resistance conditions during maximum sprint-running. Mean ± standard deviation.

Variables	Unloaded	WR 1% BM	WR 2% BM	WR 3% BM
Peak velocity (m/s)	4.68 ± 0.59	4.62 ± 0.60	4.64 ± 0.56	4.57 ± 0.64
Step length (m)	1.07 ± 0.10	1.09 ± 0.10	1.10 ± 0.10	1.09 ± 0.11
Step frequency (Hz)	4.11 ± 0.29	4.06 ± 0.22	4.03 ± 0.23*	3.99 ± 0.22*
Contact time (s)	0.173 ± 0.019	0.175 ± 0.020	0.178 ± 0.020	0.178 ± 0.022
Flight time (s)	0.076 ± 0.032	0.080 ± 0.037	0.078 ± 0.030	0.080 ± 0.037
Vertical Force (N/kg)	22.4 ± 1.51	22.4 ± 1.93	23.5 ± 3.44	23.4 ± 3.32
Horizontal Force (N/kg)	3.88 ± 0.60	3.74 ± 0.65	3.89 ± 0.49	3.76 ± 0.65
Pmax (W/kg)	18.1 ± 4.25	17.5 ± 4.69	18.2 ± 3.82	17.9 ± 4.58

* Significantly different from unloaded condition at $p < 0.05$. BM = body mass; WR = wearable resistance

Table 16. Average and step phase analysis of rotational kinematic variables for unloaded and wearable resistance conditions during maximum sprint-running. Mean ± standard deviation.

Variables and step phases		Unloaded	WR 1% BM	WR 2% BM	WR 3% BM
Thigh angular displacement (°)					
AP		68.9 ± 7.6	68.0 ± 10.0	68.8 ± 6.2	67.1 ± 10.1
MVP1		85.0 ± 8.2	82.3 ± 9.8	78.4 ± 5.7*	76.0 ± 8.9**
MVP2		80.6 ± 9.6	80.1 ± 9.5	72.1 ± 10.6*	68.7 ± 14.0*
Average		77.1 ± 6.7	75.5 ± 8.2	71.7 ± 5.5*	69.1 ± 7.8**[a]
Thigh angular velocity ($°\cdot s^{-1}$)					
AP	Extension	467 ± 73.8	439 ± 72.4	421 ± 68.1	419 ± 69.4
	Flexion	519 ± 77.3	506 ± 80.7	501 ± 72.2	472 ± 69.0
MVP1	Extension	523 ± 64.0	509 ± 69.2	466 ± 69.7	464 ± 84.3*
	Flexion	570 ± 49.6	562 ± 60.4	553 ± 68.5	508 ± 63.1*
MVP2	Extension	488 ± 76.7	475 ± 58.8	418 ± 78.4*	412 ± 97.6**
	Flexion	524 ± 66.0	530 ± 73.0	489 ± 89.2*	459 ± 57.5*
Average	Extension	457 ± 58.4	439 ± 51.6	407 ± 61.8	402 ± 70.4*
	Flexion	503 ± 36.5	499 ± 50.7	486 ± 56.8	451 ± 57.2*

* Significantly different from unloaded condition at $p < 0.05$. ** Significantly different from unloaded condition at $p < 0.01$. [a] Significantly different from 1% WR condition at $p < 0.05$. AP = Acceleration phase; AP = Acceleration phase; BM = body mass; MVP1 = initial maximum velocity phase; MVP1 = maintenance maximum velocity phase; Pmax = peak power output; WR = wearable resistance

5.4 Discussion

This study aimed to determine the acute changes from different magnitudes of WR attached distally on the thighs on kinematics and kinetics during sprinting. The main findings were that sprint-running with WR resulted in: 1) trivial to small ES changes in linear kinematics and kinetics, with average step frequency significantly decreased with loads ≥ 2% BM; and 2) moderate to large ES changes in rotational kinematics, with angular displacement and velocity of the thigh significantly decreased beyond the acceleration phase and with loads ≥ 2% BM.

Similar to previous studies that used whole leg WR loading in both NMT (134) and over ground sprints (76, 77), a significant decrease was found in average step frequency while step length was statistically unchanged with WR. Though trivial to small changes to the two determinants of step frequency (i.e. contact time and flight time) were non-significant, the coupled effects of these determinants appear to contribute to the significant difference in step frequency. As velocity is a product of step frequency and step length, the overloading of step frequency without decreasing step length suggests that ≥ 2% BM loading may be a suitable training method to overload and therefore improve the step frequency component of velocity. That is, the step frequency of sprinters training with thigh affixed WR will initially be reduced, however, the aim of training is to reproduce the baseline step frequency, so once the WR is removed there is potential for step frequency to increase. Whether this is the case and how it affects other determinants of sprint mechanics, needs to be tested.

Regarding kinetics, trivial to small ES changes ($p > 0.05$) were found in the average kinetic measures of interest. Trivial increases (4.3-4.7%) in average vertical force were found with ≥ 2% BM WR thigh loads. WR of 5% BM attached to the whole leg resulted in small ES decreases in vertical force (-1%) (134). Given that the vertical force is influenced by acceleration due to gravity, any reduction in centre of mass height, would reduce the influence of the acceleration of the body downward, which in turn affects the force. Therefore, greater leg WR loading is required to overload vertical force during NMT sprinting. This was certainly the case with trunk worn WR during NMT sprint-running, where loads of ~20% BM were required to significantly overload vertical force (36). It may be proposed that thigh WR appears to be more of a rotational and horizontal overload than vertical overload to sprinting. From previous over ground sprint studies that used whole leg WR, small increases in horizontal force (~5-6%, $p > 0.05$) and power (~1-2%, $p > 0.05$) were observed with 3% BM (77, 136). In this study, only trivial increases (≤ 0.5%) were found with 2% BM with decreases found with 1% and 3% BM, mostly likely due to the friction effect from NMT sprinting, which most likely masked any changes as compared to over ground sprinting with WR. Therefore, further over ground studies into how thigh WR effects kinetic properties of sprint-running are required.

Though trivial to small ES changes were found in linear kinematics and kinetics, moderate to large ES changes occurred in rotational kinematics with WR, suggesting thigh WR has a greater effect on the rotational action and work of the hip musculature. Though no significant changes were found during the acceleration phase in angular kinematics, beyond this phase loads of ≥ 2% BM were found to significantly decrease angular displacement and velocity, though only 3% BM significantly decreased average steps for velocity. In summary, thigh attached WR was minimally affected the acceleration phase, the WR having a greater effect during the maximum velocity phase, even with lighter loading magnitudes. This variance is most likely be explained by the increased limb angular velocities during the maximum velocity phase, which results in greater angular momentum and kinetic energy and therefore greater muscular work is required compared to the acceleration phase. This is highlighted in the significantly moderate to large ES changes found in angular kinematics, with trivial to small changes mainly found in linear step kinematics and kinetics.

A limitation of this study is that sprints were performed on an NMT and therefore the effects of WR on over ground sprinting may be different. The subjects used in this study were recreationally trained healthy males and females, and therefore the effects with different cohorts and with more proficient sprinters could be different. As a relatively small sample size was investigated, future studies may benefit from using larger cohorts. Moreover, rotational kinematics were only collected from the left leg and therefore difference between limbs may exist, however, were beyond the scope of analysis of this study.

5.5 Conclusions

The findings of this Chapter confirm that limb loaded WR provides a rotational overload that is not well quantified using linear assessment devices such as force plates. The only linear variable that was significantly affected by WR was step frequency, which is affected by rotational measures such as swing velocity and displacement i.e. loads of $\geq$ 2% BM WR attached distally to the thigh significantly reduced angular displacement and velocity of the thigh and therefore decreased step frequency. Practitioners need to be aware of the effects of WR as a rotational overload and don't load according to linear type diagnostics.

As the sprint duration increased, it can be observed that the rotational effects of WR increased and this is a function of the angular kinetic energy associated with the movement, especially the exponential effects of angular velocity, which in turn affect the rotational workload of the hip musculature in terms of accelerating-braking-re-accelerating the thigh. Practitioners need to understand that moderating the velocity of movement affects the magnitude of overload experienced by the tissues, and you can periodise training plans with this in mind. Furthermore, given the lower angular velocities during the acceleration phase, there may be a case to use higher % BM training during this phase. Such a contention needs investigation.

Finally, we propose that the NMT may have masked some of the “real” loading effects due to the friction associated with moving the belt and the incongruent results with other studies. For a better understanding of the true effects of light load variable resistance training it is recommended that over ground sprinting be the method of choice where possible. Furthermore, future studies are required to determine the longitudinal adaptation and therefore utility of using WR as a form of sprint-specific loading.

Chapter 6. Changes in Step Kinematics and Kinetics During Over Ground Sprint-Running with Thigh Wearable Resistance

This chapter comprises the following paper published in the European Journal of Sport Science.

Reference: Macadam, P, Nuell, S, Cronin, JB, Nagahara, R, Uthoff, AM, Graham, SP, Tinwala. F, Neville, J (2019). Thigh positioned wearable resistance affects step frequency not step length during 50 m sprint-running. *European Journal of Sport Science*, doi: 10.1080/17461391.2019.1641557

Author contributions: Macadam P, 80%, Nuell S, 4%, Cronin J, 4%, Uthoff A, 3%, Nagahara R, 3%, Tinwala F, 2%, Graham S, 2%, Neville J, 2%

6.0 Prelude

From the previous chapter, linear changes in kinematics and kinetics were found with incremental WR loading attached to the thighs during sprint-running on an NMT. However, as NMT and over ground sprinting do not result in the same outputs since the task constraints change with the demand to overcome the friction of the treadmill, the effects of thigh WR on over ground sprint-running properties remain unknown. Given the greater changes found with ≥ 2% BM in Chapter 5, thigh attached WR of 2% BM WR was chosen to investigate the changes in kinematics and kinetics during over ground sprint-running. Maximum effort sprints of 50 m were performed over 50 m of in-ground force plates which enabled consecutive step kinematics and kinetics to be collected and used for comparison between unloaded and WR conditions. This enabled previously unknown WR insights in step kinetics to be collected, while step kinematics had previously only been assessed during 20 m WR sprint studies. Therefore, this chapter aimed to understand how 2% BM WR thigh loading affected step kinematic and kinetic properties of over ground sprint-running. The analysis was completed from breakpoint transitions, identified over three different step phases, with the focus on load effects within each step phase for the sake of clarity.

6.1 Introduction

Step length, step frequency and ground contact time are directly related to sprint-running performance with GRF and impulse affecting changes in these variables (100, 101). Sprint-running velocity is the product of step frequency and length, both of which are mutually dependant on an optimal ratio that enables maximal sprinting speed (1, 93). An increase of both variables simultaneously is difficult due to their mutual dependency (67), thus, an increase in one variable will result in an improvement in velocity, providing the other variable does not proportionately decrease (59).

Step length is known to increase throughout the sprint until a plateau is reached during the maximum velocity phase (39, 120), however, the changes in step frequency during the acceleration phase are less clear due to individual variability (39). Step length is positively influenced by long limb lengths, whereas step frequency is positively influenced by shorter limb lengths, and low moments of inertia of the legs (39, 59). Moreover, Dorn, et al. (43) found that faster speeds (>7.0 m/s) involve higher step frequencies, which were mainly produced by large hip angular velocities in the swing phase, highlighting the importance of hip musculature affecting step frequency. Therefore, training methods that overload the hip musculature, and thus step frequency during sprint-running, may lead to beneficial performance changes. One such method of training in this manner is to attach an external load to the legs via WR, which facilitates sport-specific movement and acceleration through a full range of motion (73). Previously, WR ranging from 2.4-5.0% BM attached to the legs resulted in significant decreases in step frequency (-1.3% to -3.6%), though step length was minimally changed (-0.6% to 0.8%, $p > 0.05$) (13, 77, 136). Moreover, adding load to a limb increases its mass and moment of inertia, while simultaneously affecting potential, translational, and rotational kinetic energies (121). Therefore, thigh loading would increase the rotational inertia of the thighs, and thus it will take more muscular effort from the hip flexors, during the swing phase, and extensors, during the stance phase, to initiate and control the rotational movement of the thigh. The additional loading on the body may also increase the vertical force the athlete needs to exert on the ground to produce a flight phase (and possibly also the horizontal force). That is, sprinting with thigh WR is essentially a resistance training exercise, though the exercise is expected to be highly specific as the athlete is sprinting.

Faster sprinters are able to achieve greater speeds by striking the ground with more force and over a shorter time period than slower sprinters (67). Moreover, the ability to produce large amounts of propulsive impulse is a strong predictor of acceleration and sprint performance (89). Previous leg WR over ground sprint-running studies found increases in relative maximal horizontal force of 5.4-6.2% with leg loading of 3% BM, resulting in significantly decreased (-10.0% to -12.2%) slope of the force-velocity curve (77, 136). However, the effects of WR on impulses over each step throughout a sprint, and over distances greater than 20 m have yet to be investigated.

Given the evidence presented, investigations into the effects of sprint training methods that specifically overload the key determinates of speed, i.e. step frequency and step length, are warranted. To these ends, placing WR to the distal aspect of the thigh during the sprint would seem one such method. Therefore, given the limited research into this area the purpose of this study was to determine the acute changes in kinematic, impulse and vertical stiffness variables when 2% BM was attached distally to the thighs during over ground maximal effort sprint-running. It was hypothesised that the distal placed WR would increase the rotational inertia of the leg and consequently result in a decrease in step frequency due principally to swing phase mechanics, thus decreasing sprint velocity and increasing sprint times.

6.2 Methods

6.2.1 Experimental Design

A cross-sectional design was used to investigate the effects of WR, attached to the distal aspect of the thigh, on kinematic and impulse variables during 50 m sprint-running. Participants performed four 50 m sprints, comprised of two repetitions under each condition: 1) 2% BM of WR; 2) unloaded (i.e. 0% BM), in a randomised order from a random number generator. WR of this magnitude was chosen to provide a comparable overload to previous WR studies (77, 78, 136).

6.2.2 Subjects

Fifteen Japanese male athletes from university athletic clubs (20.9 ± 2.2 years; 66.8 ± 5.5 kg; 174.4 ± 5.1 cm; 100 m best times 11.40 ± 0.40 s; training experience 9.4 ± 2.6 years) volunteered to participate in the study. Written informed consent was obtained from the participants prior to their participation. The Auckland University of Technology Ethics Committee provided approval for this study.

6.2.3 Wearable Resistance

Participants wore Lila^{TM} Exogen^{TM} compression shorts (Sportboleh Sdh Bhd, Kuala Lumpur, Malaysia) for the duration of the testing session. These shorts enable loads of 50, 100 and 200 grams, with a Velcro backing, to be attached and used as WR. WR of 2% BM was attached to the distal aspect of each thigh, therefore 1% BM was distally placed evenly around each thigh with 2/3 of the load attached predominately to the anterior and the remaining 1/3 posteriorly (Figure 13).

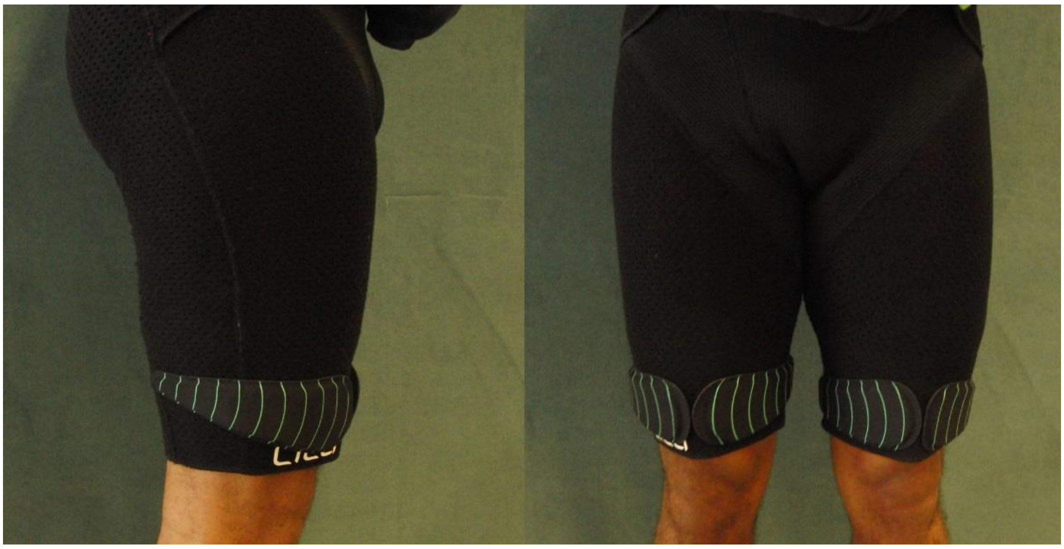


Figure 13. Wearable resistance of 2% body mass attached to the distal aspect of the thighs.

6.2.4 Procedures

The testing was conducted on an indoor Mondo track surface. Each athlete completed their own individual warm-up comprising of progressive running drills interspersed with dynamic stretching and submaximal runs (50 m) ranging from 50% to 90% of maximal effort from block starts. Following the warm-up, participants performed maximum effort 50 m sprints with and without WR from a block start wearing their own spiked sprinting shoes. For all starts, one experimenter provided a start signal using an electronic starting gun (Digi Pistol, Molten, Hiroshima, Japan), in the same manner as an official 100 m race. The start signal was to initiate the trial and recording of all the systems. Each trial was separated by five to ten minutes of passive rest.

The 50 m sprint time was measured using a photocell system (TC Timing System; Brower Timing Systems, Draper, UT, USA). Photocell units were set at the 10 m and 50 m mark (1 m above the ground) (95). A total of 54 in-ground force platforms (1000 Hz), covered by the Mondo track surface, connected to a single computer (TF-90100, TF-3055, TF-32120, Tec Gihan, Uji, Japan) measured GRFs during sprinting across a 52 m distance from approximately 1.5 m behind the starting line to the 50.5 m mark.

6.2.5 Data Analysis

As the smallest number of steps among the participants was 23, the maximum step number used for analysis was standardised to 23. This number of steps represents approximately 44 m, which was the mean distance covered by the athletes, thus kinematic and kinetic analysis relates to this distance. To understand how conditions affected different phases of the sprint, analysis was completed from breakpoint transitions, identified as step/acceleration phases: 1-4 steps, 5-14 steps, 15-23 steps, similar to Nagahara, et al. (96), Nagahara, et al. (97) and von Lieres und Wilkau, Irwin, Bezodis, Simpson and Bezodis (150). An average of all 23 steps was also compared between conditions. Due to the specific muscular and technical demands represented during the block-clearing phase of sprinting (38) this phase was not included for analysis, and subsequent analyses was performed from the first step onwards.

Kinematic variables over the 50 m sprint were calculated from GRF data using MATLAB (V2018a, Mathworks, Natick, Massachusetts, USA). In order to appropriately detect the foot strike and toe-off instants eliminating the influence of random noise, GRF signals were filtered using a forth order Butterworth low-pass digital filter with a cut-off frequency of 50 Hz (99, 101). Foot strike and toe-off instants during sprinting were identified using a vertical GRF threshold set at 20 N (101). Each step duration was determined from the foot strike of one leg to the next foot strike of the other leg. Contact time was defined as the duration of foot contact with the ground, and flight time was defined as the duration of no foot contact with the ground. Foot placement was determined as the center of pressure (COP) position at the middle of the support phase (99). The COP moved from lateral to medial during the support phase, and thus we considered that adopting the COP position at the middle of the support phase could represent the position of the medial-lateral center of the ground contact foot. Step width was the medial-lateral distance between two consecutive COP positions. Step length was calculated as the distance between ground contact foot placements for two adjacent steps in the anterior-posterior direction. Step frequency was calculated as the inverse of step duration, and step velocity was calculated as the product of step length and step frequency. Step velocity was calculated as a product of step length and step frequency (101). Maximum velocity was identified as the highest step velocity attained for each participant, which varied between steps 17 and 23 in both conditions. Vertical stiffness was calculated based on the spring mass model paradigm proposed by Morin, Dalleau, Kyrolainen, Jeannin and Belli (88) as follows:

$$\text{Vertical stiffness} = F_{max} \cdot \Delta y$$

where F_{max} = maximal ground reaction force during contact from the force plate data (in kilo Newtons); Δy = the vertical displacement of the centre of mass (in meters).

The modelled total vertical displacement of the centre of mass were calculated from:

$$\Delta y = \frac{F_{max} \cdot CT^2}{m \cdot \pi^2} + g \cdot \frac{CT^2}{8}$$

where m = subject’s BM (in kilogram); g = acceleration due to gravity (in meter per squared second); CT = contact time (in seconds).

Time integration of three-dimensional GRFs were used to calculate impulses as per previous studies (98, 99). The vertical impulse was obtained using a time integration of vertical GRF with the trapezoid formula. Propulsive and braking impulses were calculated using time integrations of the positive and negative anterior–posterior forces using the trapezoid formula. The net anterior–posterior impulse was calculated as the sum of the propulsive and braking impulses. Similarly, the net medial-lateral impulse was calculated by integrating GRFs in the medial (positive force) and lateral (negative force) directions. Impulse and vertical stiffness values for unloaded sprinting were normalised to BM. Impulse and vertical stiffness values for the WR condition were normalised to system mass, this was calculated from participant's BM plus the additional 2% BM from the WR.

6.2.6 Statistical Analyses

Standard descriptive statistics (means and SD) were reported for all statistical comparisons. The average data from the two repetitions under each condition were used for analysis. The Shapiro-Wilk statistic was used to check the data for normal distribution. Statistical differences in variables of interest across WR and unloaded conditions were determined using a paired t-test. Statistical significance was set at an alpha level of $p < 0.05$. ES, reported using Cohen's d, and 90% CI were used and described as trivial (<0.2), small (0.2-0.5), moderate (0.51-0.79) and large (>0.8) (27). ES was calculated by the mean difference between groups, dividing the result by the pooled SD, and were used to quantify the size of the difference between two groups (27).

6.3 Results

The results for split times and kinematic variables between conditions are displayed on Table 17. No statistically significant ($p < 0.05$) differences were found between unloaded and WR conditions in terms of sprint times, with small ES increases occurring with the WR condition (10 m = 1.0%, ES = 0.31, 50 m = 1.6%, ES = 0.45). When the kinematic variables across all step phase were averaged, the WR condition resulted in non-significant trivial changes (ES = -0.06 to 0.04) in step width, step length, and flight time, small decreases in step velocity (-1.5%, ES = -0.40), and step frequency (-1.7%, ES = -0.34), and moderate increases in contact time (3.2%, ES = 0.51). Regarding step phases, the WR condition resulted in moderate ($p > 0.05$) ES changes in step frequency (-2.8%, ES = -0.53, steps 5-14), and contact time (2.5%, ES = 0.57, steps 5-14). All other step phase changes were trivial or small for all other kinematic variables.

Table 17. Sprint times and kinematic changes for wearable resistance and unloaded sprint-running over multiple step phases. Mean ± standard deviation.

Variable	Step phases	Unloaded	Wearable resistance	Effect size (90% confidence intervals)
10 m time (s)	-	2.15 ± 0.08	2.17 ± 0.08	0.31 (-0.55 : 1.16)
50 m time (s)	-	6.65 ± 0.23	6.75 ± 0.25	0.45 (-0.42 : 1.30)
Step velocity (m/s)	Maximum	9.55 ± 0.42	9.36 ± 0.40	-0.46 (-1.32 : 0.40)
	Average	8.11 ± 0.31	7.99 ± 0.31	-0.40 (-1.26 : 0.46)
	1-4	5.49 ± 0.26	5.48 ± 0.27	-0.04 (-0.89 : 0.81)
	5-14	8.20 ± 0.32	8.07 ± 0.32	-0.39 (-1.25 : 0.47)
	15-23	9.19 ± 0.36	9.01 ± 0.35	-0.50 (-1.36 : 0.36)
Step length (m)	Average	1.86 ± 0.13	1.86 ± 0.11	0.02 (-0.83 : 0.87)
	1-4	1.31 ± 0.12	1.31 ± 0.10	0.04 (-0.81 : 0.89)
	5-14	1.86 ± 0.14	1.87 ± 0.11	0.07 (-0.78 : 0.92)
	15-23	2.10 ± 0.13	2.09 ± 0.11	0.06 (-0.91 : 0.79)
Step width (m)	Average	0.16 ± 0.05	0.16 ± 0.05	-0.06 (-0.91 : 0.79)
	1-4	0.30 ± 0.06	0.29 ± 0.06	-0.08 (-0.93 : 0.77)
	5-14	0.17 ± 0.06	0.16 ± 0.05	-0.11 (-0.96 : 0.74)
	15-23	0.10 ± 0.05	0.10 ± 0.05	0.04 (-0.81 : 0.89)
Step frequency (Hz)	Average	4.37 ± 0.25	4.30 ± 0.19	-0.34 (-1.20 : 0.52)
	1-4	4.21 ± 0.31	4.18 ± 0.27	-0.12 (-0.97 : 0.74)
	5-14	4.42 ± 0.26	4.31 ± 0.19	-0.53 (-1.39 : 0.34)
	15-23	4.40 ± 0.23	4.32 ± 0.19	-0.36 (-1.21 : 0.50)
Flight time (s)	Average	0.109 ± 0.010	0.109 ± 0.008	0.04 (-0.81 : 0.89)
	1-4	0.077 ± 0.011	0.074 ± 0.010	-0.24 (-1.09 : 0.62)
	5-14	0.109 ± 0.011	0.110 ± 0.009	0.09 (-0.76 : 0.94)
	15-23	0.123 ± 0.010	0.124 ± 0.008	0.10 (-0.75 : 0.95)
Contact time (s)	Average	0.121 ± 0.007	0.125 ± 0.007	0.51 (-0.36 : 1.37)
	1-4	0.163 ± 0.013	0.167 ± 0.013	0.31 (-0.54 : 1.17)
	5-14	0.119 ± 0.006	0.122 ± 0.007	0.57 (-0.30 : 1.44)
	15-23	0.105 ± 0.006	0.108 ± 0.006	0.46 (-0.40 : 1.32)

Table 18. Relative impulses and vertical stiffness changes for wearable resistance and unloaded sprint-running over multiple step phases. Mean ± standard deviation.

Variable	Step phases	Unloaded	Wearable resistance	Effect size (90% confidence intervals)
Propulsive impulse (N·s/kg)	Average	0.431 ± 0.024	0.430 ± 0.024	-0.03 (-0.88 : 0.82)
	1-4	0.866 ± 0.050	0.871 ± 0.054	0.10 (-0.75 : 0.95)
	5-14	0.395 ± 0.026	0.389 ± 0.024	-0.25 (-1.10 : 0.61)
	15-23	0.277 ± 0.023	0.280 ± 0.020	0.13 (-0.72 : 0.98)
Breaking impulse (N·s/kg)	Average	-0.122 ± 0.020	-0.128 ± 0.018	-0.32 (-1.18 : 0.54)
	1-4	-0.040 ± 0.017	-0.040 ± 0.013	0.04 (-0.81 : 0.89)
	5-14	-0.099 ± 0.020	-0.107 ± 0.019	-0.43 (-1.29 : 0.43)
	15-23	-0.185 ± 0.029	-0.191 ± 0.026	-0.24 (-1.09 : 0.61)
Net anterior-posterior impulse (N·s/kg)	Average	0.309 ± 0.018	0.302 ± 0.017	-0.39 (-1.25 : 0.47)
	1-4	0.826 ± 0.057	0.831 ± 0.057	0.10 (-0.75 : 0.95)
	5-14	0.296 ± 0.020	0.282 ± 0.019*	-0.73 (-1.61 : 0.15)
	15-23	0.093 ± 0.018	0.089 ± 0.015	-0.24 (-1.09 : 0.61)
Net medial-lateral impulse (N·s/kg)	Average	0.091 ± 0.065	0.089 ± 0.069	-0.03 (-0.88 : 0.82)
	1-4	0.295 ± 0.083	0.284 ± 0.096	-0.12 (-0.97 : 0.73)
	5-14	0.096 ± 0.075	0.094 ± 0.078	-0.04 (0.89 : 0.81)
	15-23	-0.006 ± 0.062	-0.003 ± 0.064	0.05 (-0.80 : 0.90)
Vertical impulse (N·s/kg)	Average	2.26 ± 0.13	2.29 ± 0.10	0.27 (-0.58 : 1.12)
	1-4	2.29 ± 0.17	2.31 ± 0.15	0.09 (-0.76 : 0.94)
	5-14	2.24 ± 0.13	2.28 ± 0.10	0.32 (-0.54 : 1.17)
	15-23	2.27 ± 0.12	2.31 ± 0.10	0.30 (-0.55 : 1.16)
Vertical stiffness (kN·m·kg^{-2})	Average	0.735 ± 0.082	0.695 ± 0.071	-0.52 (-1.39 : 0.34)
	1-4	0.398 ± 0.061	0.378 ± 0.062	-0.33 (-1.18 : 0.53)
	5-14	0.720 ± 0.076	0.679 ± 0.068	-0.57 (-1.44 : 0.30)
	15-23	0.906 ± 0.108	0.858 ± 0.094	-0.47 (-1.33 : 0.39)

The changes in impulse and vertical stiffness values between conditions can be observed in Table 18. WR resulted in a significant decrease (-4.8%, ES = 0.73) in net anterior-posterior impulses in steps 5-14, with trivial to small ES found during the other step phases (-2.3% to 0.7%). All other kinetic comparisons between unloaded and WR conditions were found to be non-significant. For average and all step phases, trivial changes were found in medial-lateral impulses (-3.8% to 2.1%), and trivial to small changes in propulsive (-1.6% to 1.1%), braking (0-7.5%), and vertical impulses (0.9-1.8%) with the WR condition. While small to moderate ES decreases in vertical stiffness were found during WR sprint-running with an average decrease of -5.5% (ES = -0.52).

6.4 Discussion

The purpose of the study was to investigate the acute effects of distally thigh positioned WR on kinematic, impulse and vertical stiffness variables during over ground maximal 50 m sprint-running. From our findings, thigh WR had a greater effect on step frequency (ES = -0.12 to -0.53) than step length (ES = 0.04-0.07), resulting in longer contact times (3.2%) and decreased net anterior-posterior impulses (-2.3%) and vertical stiffness (-5.5%).

The initial hypothesis that WR would decrease step frequency due to overloading the hip musculature in the swing phase, thus decreasing sprint velocity and times was partially supported given some of the ES reported. Though sprint times were slower (10 m = -1%, 50 m = -1.6%), the changes were not statistically significant. Findings from this study are comparable to previous leg WR studies (leg WR of 3-5% BM), which found no significant differences in sprint times at 10 m (77, 136). However, previous studies have not measured sprint times beyond 20 m, thus comparisons to this study are limited. In contrast, maximum velocity was significantly reduced (-3.6% to -6%) in the aforementioned two WR studies, while decreased maximum velocity (-2.0%) was found in this study, it was not statistically significant. These differences in velocity most likely relate to greater WR loading (2% vs. 3-5% BM) and differences in placements (thigh vs whole leg), which resulted in greater rotational inertia.

WR sprint-running affected the average step frequency (-1.7%) more than step length (0%), contributing to the decreased sprint times and velocity. At higher sprinting velocities, corresponding to the second acceleration phase (i.e. steps 5-14), the body is in a more upright position than at the initial phase. Therefore, with WR attached distally to the thighs, athletes would have been required to overcome a greater amount of rotational work due to greater limb velocities and angular momentum. Despite the light loads, this probably overloaded the hip flexor musculature reducing the hip angular velocity during the swing, resulting in a decreased step frequency. Moreover, this may have contributed to the moderately reduced step velocity during steps 15-23. These results are in accordance with other leg loaded WR sprint studies that found step frequency was significantly decreased (-1.3% to -3.6%) and step length was unchanged (77, 136). Though the average step width and flight time values were unchanged ($p > 0.05$), the WR resulted in participants spending more time on the ground as shown in the moderately longer average contact times. Therefore, from the findings in this study, and the aforementioned other WR studies, it appears that WR attached to the legs had a greater overload effect on step frequency and contact times, with step length being unaffected.

The WR condition resulted in a significant decrease (-4.8%, ES = 0.73) in net anterior-posterior impulses in steps 5-14, with trivial to small ES found during the other step phases. Since the braking and propulsive impulses determine the net anterior-posterior impulse, sprint performance may be improved by minimising the braking force generated at ground contact (55, 91) and thus modifying net impulses by manipulating the braking and propulsive impulses independently (Morin et al., 2015). During the WR condition, foot strike may have occurred earlier recognised with longer contact times leading to greater breaking impulse. Horizontal velocity of the foot prior to touchdown has been proposed as the main determinant of braking forces (55), therefore, WR may be a training tool to overload net anterior-posterior impulses, resulting in positive adaptations as the athletes has to overcome the additional loading.

Vertical stiffness was decreased with WR, with moderate ES changes found in steps 5-14 (-5.5%) and average steps (-5.7%). The additional loading may have increased flexion at the knees or ankles during the support phase contributing to the longer contact times and decreased step frequency. Congruently, a study with 3% BM leg WR was found to significantly decrease vertical stiffness (-6.2%) during 20 m sprint-running (77). Moreover, WR may provide a training stimulus to overload vertical stiffness, which causes greater acute centre of mass displacement and effectively overloads the stretch shortening cycle, thus may be used to reduce leg compliance and improve sprint performance. However, acute and longitudinal research designs are required to investigate such contentions.

Previous researchers (96, 97, 150) have identified two acceleration transition points (steps 4 and 14), thus track speed has been broken into three phases. Findings from this study reveal that WR had a minimal effect in the first acceleration phase, however, as the velocity increased and the trunk became more upright, WR seems to provide a greater overload to sprint mechanics. During the second and third phases, the distal thigh WR may have overloaded thigh angular velocity and displacement due to the greater thigh rotational displacement and velocity when the body is upright. This contention likely supported by the changes to several variables during steps 5-14, with significantly decreased net anterior-posterior impulse and moderately reduced step frequency and vertical stiffness, coupled with the moderately increased ground contact time found with WR.

Moreover, the range of hip flexion-extension was previously shown to decrease slightly in the third acceleration phase (96). This may explain why differences in variables between conditions were trivial to small in steps 15 to 23.

Though measurements of kinematic variables were collected in this study, the effect of WR on joint kinematics (particularly thigh angular velocities and displacement) are beyond this Chapter. Therefore, future research is required to assess whether the distal thigh WR improves the piston-like action of the legs from motion capture video analysis**,** electromyography analysis, and with training studies required to evaluate adaptation in sprinting performance.

6.5 Conclusions

WR sprinting requires athletes to overcome a greater amount of rotational inertia due to the distal load placement on the thighs. This was particularly evident as velocity increased during the second acceleration phase of steps 5-14. WR offers athletes a means to target step frequency, net anterior-posterior impulses, and vertical stiffness, during sprint specific form training, whilst not affecting step length. Given the importance of these two step variables in attaining sprinting speeds, and that the thigh moment inertia increases with WR, this form of loading could be a suitable training tool to overload the hip flexors to improve sprint mechanics. Additional acute research is needed to investigate the effects of other load magnitudes and placements (e.g. shank), as well as longitudinal research to determine if our contentions are in fact true.

Chapter 7. Mechanical Rotational Workload Responses During Over Ground Sprint-Running with Thigh Wearable Resistance

This chapter comprises the following paper published in Sports Biomechanics.

Reference: Macadam, P., Cronin, J., Uthoff, A., Nagahara, R., Tinwala, F., Zois, J., Diewald, S., Neville, J. Thigh loaded wearable resistance increases sagittal plane rotational work of the thigh resulting in slower 50 m sprint times. *Sports Biomechanics. d*oi: 10.1080/14763141.2020.1762720

Author contributions: Macadam P, 80%, Cronin J, 5%, Uthoff A, 3%, Nagahara R, 3%, Tinwala F, 2%, Zois, J 2%, Diewald S, 2%, Neville J, 2%

7.0 Prelude

Fundamental understanding of sprint-running mechanics is often linear in quantification, with linear outcome measures the result of rotation at the joints. From Chapter 5, the rotational action of the thigh was significantly overloaded with thigh WR during NMT sprint-running. While from Chapter 6, thigh WR resulted in moderate ES changes in linear step kinematics and kinetics during over ground sprint-running. However, the changes in rotational overload effects of WR are unknown during over ground sprint-running. Of interest therefore is understanding the effects of WR using IMU technology, on the rotational action of the thigh during sprint-running. The following chapter investigated changes in rotational kinematics and rotational work over 50 m sprint-running with 2% BM WR attached to the thighs compared to unloaded sprint-running. Rotational kinematics and work were separated into step phases to assess the load effects within each step phase.

7.1 Introduction

Sprint-running is often quantified via linear measures; however, it is the product of the angular motion of the legs and arms. It would therefore make sense to find training methods to overload angular motion specific to sprinting, to maximise sprint specific adaptation. One such training modality is WR, which involves athletes moving micro-loads that are attached to the limbs in some manner. There has been a re-emergence of the use of this technology, especially with regards to sprint research, however, one of the challenges associated with WR limb loading is quantifying the workload given the angular overload it provides. The addition of WR to a limb such as the thigh, is thought to increase the rotational inertia and hence the turning forces/torques required to move this additional load, and hence it is thought rotational work at the hip would be increased. However, it may be that there is a concomitant decrease in angular displacement with such loading, and hence workload does not in fact increase but rather stays the same or decreases. Of interest to the authors therefore is understanding the effects of WR on angular work of the thigh during sprinting.

Three studies have assessed the acute rotational work effects of WR attached to the thigh during treadmill running at speeds of 2.68-3.3 m/s. Thigh loads of 0.6% and 1.4% BM were used in two studies (80, 81), while Myers and Steudel (94) used WR totalling 4.8-5.8% BM. The positioning of the WR ranged from proximal from the hip to mid-thigh in these previous studies. Mechanical workload was significantly increased (9.5%) with 1.4% BM WR but did not significantly differ from unloaded running (2.5%) with the lighter WR of 0.6% BM (80). Though thigh loading increased the moment of inertia by 2%, no significant changes in work values were reported (81). The greater loading of 4.8-5.8% BM significantly increased the entire limb's moment of inertia by 1%, and was reported to have increased mechanical work, however, the authors did not quantify these changes (94). As can be observed there are no systematic trends in the results related to the effect of thigh worn WR on rotational mechanical workload. This can be attributed in part to: 1) magnitude of loads (0.6 to 5.8% BM); 2) placement of loads (proximal to mid-femur) which effects rotational inertia; 3) the different methodologies used (work load calculations); and, 4) the duration and speeds of the running phase investigated.

The previous thigh WR running studies (80, 81, 94) collected rotational kinematics from standard definition video. However, recent developments in technology have enabled rotational kinematics to be collected from a wearable IMU, which enable a greater volume of capture data to be collected outside of a laboratory setting, providing a more ecologically valid method for data collection. Thigh attached IMUs were previously used to collect rotational kinematics of the thigh during running (108) and sprinting (128, 129). Previous IMU sprint studies have found that rotational kinematics measures were valid with root mean square error measures in shank angular displacement (≤ 5%) and velocity (≤ 10%), and trunk angular displacement (≤ 5%) (14, 23), and can be used to reliably report trunk angular displacement (≤ 6%) (14).

Though acute rotational work effects from WR have been assessed at submaximal running speeds (80, 81, 94), WR thigh loading has yet to be investigated at maximal effort sprint-running speeds. No studies to date have quantified mechanical workload with WR thigh loads at speeds greater than 3.3 m/s. As intimated previously, it is important to understand whether such loading actually provides a mechanical overload of sprint specific musculature, as the determinants of rotational work (rotational inertia, acceleration and displacement), may be affected in a manner where the net work from thigh loading is in-substantial i.e. increases in rotational inertia may be negated by a counteracting influence of decreased angular displacement or velocity. Of interest to the authors therefore is understanding the effects of WR using IMU technology, on angular work of the thigh during sprinting. It was hypothesised that the effects of rotational inertia ($I = mr^2$) would be greater than any decrease in angular acceleration and displacement, hence WR would provide a sprint specific increase in mechanical workload of the thigh musculature.

7.2 Methods

7.2.1 Procedures

A cross-sectional study design was used to investigate the effects on sprint kinematics and kinetics when WR was attached to the distal aspect of the thigh during sprint-running. Fifteen athletes from university athletic clubs (21.0 ± 2.5 years; 174 ± 4.1 cm; 67.5 ± 5.4 kg; 9.2 ± 2.5 training years; 11.3 ± 0.5 s 100 m personal best time) volunteered to participate in the study. Written informed consent was obtained from the participants prior to their participation. The Institutional Ethics Committee of Auckland University of Technology provided approval for this study.

Following a self-organised warm-up, participants performed maximum effort 50 m sprints with and without WR on an indoor track from starting blocks wearing spiked shoes. Participants performed four trials of a 50 m sprint, comprised of two repetitions under each condition: 1) WR 2% BM; and 2) unloaded (i.e. UL = 0% BM). The order of the conditions was randomised with a random number generator. Each trial was separated by ten minutes of passive rest.

7.2.2 Equipment

Participants wore Lila™ Exogen™ compression shorts (Sportboleh Sdh Bhd, Malaysia) for the duration of the testing session. The Exogen™ exoskeleton shorts enabled loads (with Velcro backing) of 0.05-0.2 kg to be attached. Prior running WR thigh studies placed the loads mid-thigh to proximal (80, 94). Given there would be greater inertial property changes of the limb with a more distal loading, WR totalling 2% BM was attached to the distal aspect of each thigh to increase the moment of inertia from the hip. Therefore 1% BM was placed evenly around each thigh with 2/3 of the load attached predominately anterior and the remaining 1/3 posterior (Figure 14).

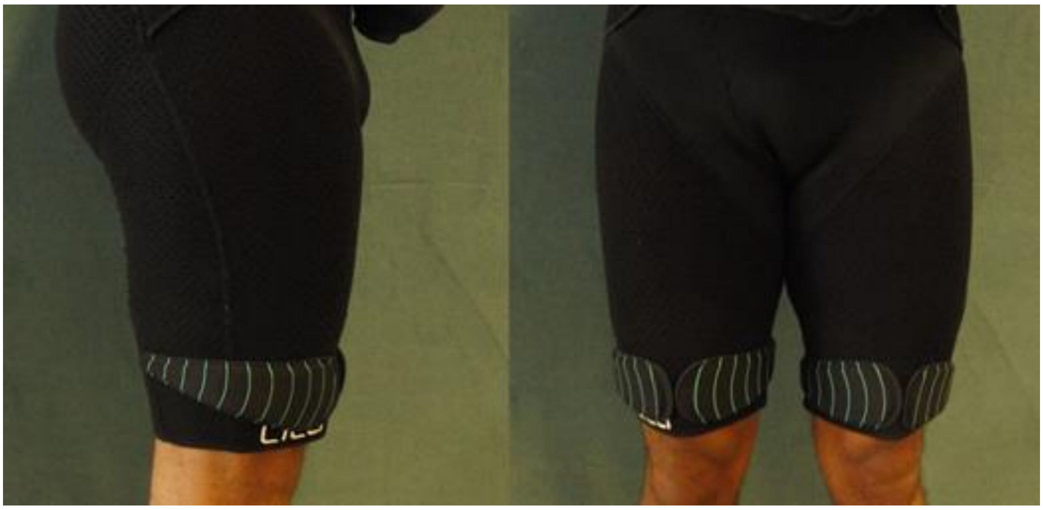


Figure 14. Wearable resistance totalling 2% BM (i.e. 1% body mass per leg) attached distally to the thigh.

The 10 m and 50 m sprint times were measured using a photocell system (TC Timing System; Brower Timing Systems, Draper, UT, USA). Photocell units were set at the 10 m and 50 m mark, which were initiated by an electric starting gun (Digi Pistol, Molten, Hiroshima, Japan).

An IMU (IMeasureU Limited, Auckland, New Zealand) consisting of a ± 16g 3-axis accelerometer, ±2000°/s 3-axis gyroscope, and a ±1200μT 3-axis magnetometer was used to collect sagittal plane rotational kinematics from the left thigh. Data were logged to the onboard memory of the IMU at 500 Hz for the duration of the trials, and then downloaded after each session for processing. The accelerometer was calibrated using gravity vectors recorded in each of the primary orientations, and the gyroscope was factory calibrated. The IMU was attached to the middle and lateral surface of the thigh, corresponding to the mid-point between the greater trochanter and lateral epicondyle of the femur, using elastic straps with tape placed onto the strap and leg to minimize skin and clothing artefact. Acceleration and rotational velocity data were imported into MATLAB (V2019b, Mathworks, Natick, Massachusetts, USA). Orientation of the sensors were calculated using a complimentary filer (Matlab 2019b). The sensor-fusion algorithm was chosen to minimize the effects of gyroscope drift and accelerometer noise. The recorded waveforms from the IMU for kinematics of the thigh were separated by steps by identifying the maximum flexion and extension (thigh range of motion) in the Z-axis, corresponding to the sagittal plane. Only a local reference frame was needed for the analysis, therefore the magnetometer data was not utilized. Cross-over movement from other planes was assumed to be minimal.

7.2.3 Data Analysis

As the smallest number of steps collected from the left leg among the participants was 10 during the 50 m sprint, therefore the maximum step number used for analysis was standardised to 10. To understand how conditions affected different phases of the sprint, analysis was completed from breakpoint transitions, identified as step acceleration phases 1: 1-2 steps, 2: 3-6 steps, 3: 7-10 steps. This analysis was similar to the bilateral analysis used by Nagahara, et al. (96), Nagahara, et al. (97) and von Lieres und Wilkau, et al. (150). An average of all 10 left steps was also compared between conditions to reflect the cumulative work. Due to the specific muscular and technical demands represented during the block-clearing phase of sprinting (38) this phase was not included for analysis, and analyses were performed from the first step onwards.

Using orientation data obtained from the IMU, rotational work was determined by quantifying the changes in sagittal plane rotational kinetic energy. The dominant acceleration movement when wearing a hip attached sensor was in the flexion-extension direction, and movement in this plane represents the best single-axis indicator for predicting energy expenditure (149). This rotational work method is similar to previous studies (81, 94) as follows:

rotational work = $\frac{1}{2}I\omega^2$

Where rotational work (J·s = $kg{\cdot}m^2{\cdot}s\text{\textasciicircum}^{-1}$), I = moment of inertia ($kg{\cdot}m^2$), and ω = angular velocity of the segment (radians/s). This J·s describes the amount of action occurring through the summation of energy over time.

Moment of inertia for the thigh mass and length were obtained from mathematical modelling approach from Japanese male athletes (2). The value of the moment of inertia was obtained from the following formula:

$I = mk^2$

Where m = total segment mass, k = distance of the radius of gyration. The radius of gyration represents the object's mass distribution with respect to a given axis of rotation. It is the distance from the axis of rotation to a point at which the mass of the body can theoretically be concentrated without altering the inertial characteristics of the rotating body. Due to the specific short lengths, the WR was placed at the end of the shorts, equivalent to approximately 80% distal from the hip joint centre as shown by dashed line in Figure 15.

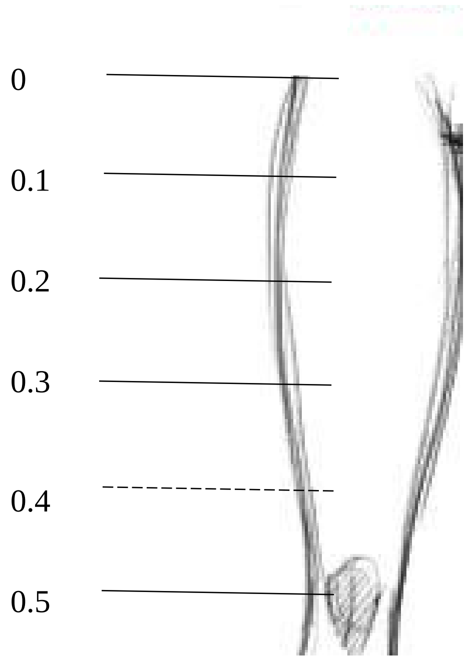


Figure 15. Example from a thigh of 0.5 m length and 7 kg mass. Dashed line shows wearable resistance placement.

Example calculation of moment of inertia for unloaded and WR conditions from 70 kg subject with 0.5 m thigh length, therefore 700 g was added as WR:

Unloaded I = $(2.0kg)(0.1m)^2 + (2.0kg)(0.2m)^2 + (1.5kg)(0.3m)^2 + (1.5kg)(0.4m)^2 + (1.0kg)(0.5m)^2$

Wearable resistance I = $(2.0kg)(0.1m)^2 + (2.0kg)(0.2m)^2 + (1.5kg)(0.3m)^2 + (2.2kg)(0.4m)^2 + (1.0kg)(0.5m)^2$

7.2.4 Statistical Analysis

Standard descriptive statistics (means and SD) were reported for all statistical comparisons. The average data from the two repetitions under each condition were used for analysis. The Shapiro-Wilk statistic was used to check the data for normal distribution. ES statistics (reported using Cohen's d) and 90% CI determined the magnitude of differences between the two conditions with values reported as trivial (<0.2), small (0.21-0.5), moderate (0.51–0.79) or large (>0.8) (27). ES was calculated by the mean difference between groups, dividing the result by the pooled SD, and were used to quantify the size of the difference between two groups (27). Statistical differences in variables of interest across WR and unloaded conditions were determined using a paired t-test. Statistical significance was set at an alpha level of $p < 0.05$.

Test-retest reliability of the cumulative rotational kinematics were assessed from two trials with each condition using CV and ICC with 90% CI calculated for each variable. The CV was calculated from (SD / Mean) *100. The current investigation set reliability thresholds of CV ≤ 10% (6), ICC ≥ 0.70 (83).

7.3 Results

The CVs (<9%) and ICCs (>0.92) were found to be reliable for both conditions and for all variables measured (Table 19).

Table 19. Test-retest reliability based on coefficient of variation (CV) and intraclass correlation (ICC) with 90% confidence intervals (CI) for rotational kinematics.

Variables	Unloaded		Wearable resistance	
	CV (%)	ICC (90% CI)	CV (%)	ICC (90% CI)
Flexion angular displacement	6.6	0.94 (0.89-0.98)	7.0	0.93 (0.88-0.98)
Extension angular displacement	6.0	0.96 (0.91-0.98)	6.3	0.94 (0.89-0.97)
Flexion angular velocity	8.8	0.95 (0.91-0.99)	9.0	0.92 (0.87-0.98)
Extension angular velocity	8.5	0.95 (0.87-0.98)	8.8	0.93 (0.86-0.97)

Sprint times were increased with the WR condition at 10 m (1.4%, ES = 0.38, p = 0.058) and significantly at 50 m (1.9%, ES = 0.55, p = 0.042) compared to the unloaded condition (Table 20).

No significant differences in angular displacement of the thigh occurred during any step phases with trivial to small ES increases (0.6-3.4%) reported (Table 21). Regarding angular velocity of the thigh, no significant changes were found in the extension movement (0.9%, ES = 0.04, p = 0.742) in step phase 1, however, flexion was significantly decreased (-8.0%, ES = 0.48, p = 0.013) with WR during this phase (Table 22). During step phase 2, extension (-3.6%, ES = 0.33, p = 0.000) and flexion (-5.5% ES = 0.51, p = 0.000) angular velocities were decreased with WR. Similarly, WR resulted in decreased extension (-2.3%, ES = 0.26, p = 0.037) and flexion (-4.6%, ES = 0.46, p = 0.000) angular velocities during step phase 3, and cumulatively (extension -2.5%, ES = 0.17, p = 0.003, flexion -5.6%, ES = 0.44, p = 0.000).

Inertia of the thigh with WR (0.494 kg·m^2) was found to be significantly increased by 14.8% (ES 0.66, p = 0.001) compared to the unloaded thigh (0.421 kg·m^2). Rotational work was significantly increased during all phases of the sprint (9.8-18.8%, ES = 0.09-0.55, p = 0.00) compared to the unloaded sprint condition (Table 23).

Table 20. Sprint times (s) changes for unloaded and wearable resistance sprint-running. Mean ± standard deviation.

Sprint distance	Unloaded	Wearable resistance	Effect size (90% CI)
10 m (s)	2.15 ± 0.07	2.18 ± 0.08	0.38 (-0.36: 1.09)
50 m (s)	6.64 ± 0.23	6.78 ± 0.25 *	0.55 (-0.19: 1.32)

* Significant difference from unloaded condition. CI = confidence interval

Table 21. Angular displacement (°) changes of the thigh for unloaded and wearable resistance sprint-running. Mean ± standard deviation.

Step acceleration phase	Extension/ Flexion	Unloaded	Wearable resistance	Effect size (90% CI)
1	Extension Flexion	80.3 ± 14.0 76.4 ± 9.02	81.6 ± 9.09 79.2 ± 12.1	0.08 (-0.78:065) 0.22 (-0.47:0.97)
2	Extension Flexion	98.7 ± 8.11 98.1 ± 7.99	99.9± 6.86 98.9 ± 7.57	0.04 (-0.68:0.75) 0.11 (-0.62:0.82)
3	Extension Flexion	100 ± 7.53 99.5 ± 7.88	102 ± 7.25 101 ± 7.73	0.26 (-0.46:0.97) 0.24 (-0.48:0.95)
Cumulative	Extension Flexion	95.9 ± 8.42 93.8 ± 7.38	96.4± 7.81 95.8 ± 6.75	0.08 (-0.65:0.78) 0.25 (-0.43:0.97)

* Significant difference from unloaded condition. CI = confidence interval

Table 22. Angular velocity (°/s) changes of the thigh for unloaded and wearable resistance sprint-running. Mean ± standard deviation.

Step acceleration phase	Extension/ Flexion	Unloaded	Wearable resistance	Effect size (90% CI)
1	Extension Flexion	523 ± 110 663 ± 94.0	527 ± 117 611 ± 121*	0.04 (-0.68:0.75) 0.48 (-0.26:1.19)
2	Extension Flexion	705 ± 81.5 779 ± 97.8	680 ± 68.7* 737 ± 64.8*	0.33 (-0.40:1.04) 0.51 (-0.23: 1.22)
3	Extension Flexion	754 ± 77.4 804 ± 89.8	734 ± 77.0* 769 ± 58.1*	0.26 (-0.47:0.97) 0.46 (-0.27:1.17)
Cumulative	Extension Flexion	688 ± 121 766 ± 95.3	671 ± 113* 725 ± 90.2*	0.17 (-0.58:0.86) 0.44 (-0.29:1.15)

* Significant difference from unloaded condition. CI = confidence interval

Table 23. Rotational work (J·s) changes of the thigh for unloaded and wearable resistance sprint-running. Mean ± standard deviation.

Step acceleration phase	Extension/ Flexion	Unloaded	Wearable resistance	Effect size (90% CI)
1	Extension Flexion	136 ± 44.1 158 ± 45.5	162 ± 59.9* 175 ± 51*	0.42 (-0.25:1.19) 0.35 (-0.36:1.07)
2	Extension Flexion	162 ± 51.7 186 ± 57.7	194 ± 69.6* 211 ± 64.7*	0.46 (-0.21:1.24) 0.40 (-0.31:1.12)
3	Extension Flexion	165 ± 50.3 195 ± 60.7	203 ± 70.5* 225 ± 66.6*	0.53 (-0.13:1.32) 0.44 (-0.27:1.17)
Cumulative	Extension Flexion	158 ± 49.5 185 ± 55.8	192 ± 67.0* 210 ± 60.8*	0.49 (-0.17:1.28) 0.41 (-0.30:1.14)

7.4 Discussion

This study aimed to determine the acute changes, measured from an IMU, on rotational kinematics and sprint performance when WR of 2% BM was attached to thighs during over ground maximal sprint-running. The main findings were that sprint-running with WR attached to the thighs resulted in: 1) increased sprint times at 10 m (1.4%, ES = 0.38) and significantly increased 50 m times (1.9%, ES = 0.55); 2) increased angular displacement (0.6-3.4%, ES = 0.04-0.26), and significantly decreased angular velocity (-2.5% to -8.0%, ES = 0.17-0.51), with greater changes in flexion (ES = 0.44-0.51) than extension (ES 0.04-0.33) movements; and, 3) significantly greater rotational work during all phases of the sprint (9.8-18.8%, ES = 0.35-0.53). These results support the hypothesis that loading the thighs using WR would affect angular displacement and angular velocity of the thigh, however, the effects of the moment of inertia was greater than these reductions, resulting in increased rotational work of the hip musculature. Therefore, it appears that WR significantly overloads thigh rotational movements, resulting in a sprint-specific overload as evidenced by increased 50 m times.

The findings regarding sprint times from this study are comparable to previous studies with whole leg WR (2.4-5% BM) which found no significant changes in sprint times at 10 m, however, beyond 10 m significantly increased sprint times were reported (13, 77, 134). Therefore, it appears that as a consequence of the increase in the rotational work of the thighs, sprint performance is more affected by the addition of WR as the sprint distance increases. Given the work-energy relationship, this makes sense, as velocity of movement affects angular kinetic energy and therefore mechanical work i.e. the kinematic and kinetic effects of WR increase with velocity of movement.

Changes to angular displacement were trivial to small. Therefore, it seems that the range of motion is similar between unloaded and thigh worn WR, the increased rotational inertia minimally affecting angular displacement. Given these changes, or lack of, and in conjunction with other studies that have reported non-significant changes to step length with leg WR (77, 134), it appears that thigh WR results in minimal effects to angular displacement and therefore step length.

Interestingly the time to move through these ranges of motion is slower, the increased rotational inertia having a greater influence on angular velocity in all phases of the sprint (~5-8%, $p < 0.05$). Though both flexion and extension actions were significantly decreased in all step phases (except extension in step phase 1) it seems the rotational inertia was more influential during hip flexion. Therefore, it could be proposed that WR may be a means for overloading and subsequently strengthening hip flexors rather than hip extensors. The greater overload changes between movements would seem logical as the flexor motion is an anti-gravity action and any additional thigh loading will need to be moved against gravity, whereas the extension moments are not impacted as much by gravity. Loading the thigh most likely influenced the acceleration – deceleration - re-acceleration of the thigh for each step, which in turn affects the angular velocity of the limbs and therefore slower step frequencies result i.e. slower swing phase velocity, which compromises step frequency. These findings align with other sprint studies where step frequency significantly decreased with leg loaded WR (77, 134).

Royer and Martin (121) previously noted that adding load to a limb increased its mass and moment of inertia. This was certainly the case with distal attached thigh WR in the current study resulting in a significantly increased moment of inertia of the thigh by ~14% compared to an unloaded thigh. From the previous running WR studies (81, 94), the moment of inertia for the entire leg increased by 1% with ~5% BM and by 2% with 0.6% BM, highlighting differences in methodologies between the studies, particular related to the distance of the WR in relation to the hip joint axis in the sagittal place. Moreover, as the prior studies were completed at treadmill running speeds and used a more proximal placement compared to the more distal placed WR in this study, greater inertia changes would be expected as the load is placed further from the hip joint and faster running speeds were achieved. Consequently, the effects on rotational work were significantly greater (10-18.3%, ES = 0.09-0.55) throughout all phases of the sprint.

Findings from this study relate to the rotational work calculation being based on the joint and segment approach of the thigh, however, this method does not measure work done elsewhere, such as passive wobbling of viscera, or the motion of unmeasured joints/segments (e.g. trunk and arms).

Assuming rigid-body segments, peripheral work changes reflect body movements relative to the center of mass, though this estimate fails to capture energy changes due to non-rigid-body motion relative to each individual body segment's center of mass (e.g. deformation of the thigh segment that does not contribute to motion of the thigh's center of mass). Linear kinetic and potential energy are not accounted for with this analysis. Moreover, only one plane of movement was analysed, though there will still be some movement in other planes that is not being accounted for, it was assumed to be minimal.

7.5 Conclusions

WR of 2% BM results in the musculature of the hip having to work harder to maintain angular displacement and velocity, whilst trying to sustain linear speed. Angular displacement and therefore step length are less affected by rotational inertia, and angular velocity and therefore step frequency are more affected. It also appears WR produces a greater flexor overload, though extensors are still significantly overloaded. Rotational kinematic findings add to the previous step kinematic studies and enable further understanding of how WR affects sprint performance. Moreover, the results with 2% BM WR aid in adding to the load spectrum analysis from prior sprint WR studies.

Sprinting with thigh WR provides a specific sprint training tool to significantly overload the rotational work experienced at the thighs, therefore, this form of loaded sprinting is essentially a resistance training exercise performed at high velocity, the resisted motion highly specific to sprint running. Beyond the initial take-off steps and early acceleration phase, the cumulative effect of thigh WR is that athletes are required to produce a greater amount of rotational work to overcome the additional inertia of the thigh, which in turn leads to increased sprint times. With repeated and systematic use of WR it is expected that athletes will adapt to the overload and the rotational musculature of the hip become stronger specific to the mechanics of sprinting. With removal of the WR faster sprint times should ensue. Future studies, however, are required to assess long-term adaption to changes in rotational kinematics and sprint-performance with this form of sprint-specific loading.

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Chapter 8. Thigh Positioned Wearable Resistance Improves 40 m Sprint Performance: A Longitudinal Single Case Design Study

This chapter comprises the following paper published in the Australian Journal of Strength and Conditioning.

Reference: Macadam, P., Nuell, S., Cronin, J., Diewald, S., Neville, J. (2019). Thigh positioned wearable resistance improves 40 m sprint performance: a longitudinal single case design study. Journal of Australian Strength & Conditioning. 27(04):39-45

Author contributions: Macadam P, 85%, Nuell S, 5%, Cronin J, 5%, Diewald S, 3%, Neville J, 2%.

8.0 Prelude

Previously from Chapters 5, 6, and 7, acute small to moderate effect size changes in net anterior-posterior impulse, vertical stiffness, step frequency and contact time were found with thigh attached WR during sprint-running. Moreover, significant large changes in rotational kinematics were found with thigh attached WR. These findings suggest that for athletes seeking to overload rotational kinematics, vertical stiffness and step frequency and develop anterior-posterior impulse during accelerated sprinting, WR enables the overload of these qualities. However, whether these acute findings translate to actual changes that are meaningful to sprint performance are unknown, a longitudinal training intervention therefore needed to determine the efficacy of such training. Examining the training effects of a group of subjects over a long-term period is challenging. Therefore, the following study examined the training effects of WR using a single subject case design over a 5 week training period.

8.1 Introduction

To improve sprint-running performance an athlete commonly focuses on two aspects of training: the first aims to improve the magnitude and rate of effective force output; and, the second aims to improve the technical efficiency of the sprint action (25). Although all joints within the lower extremity contribute to sprint-running performance, the hip joint is the fulcrum of the leg levers that propels the body forward (43, 127). During sprint-running, hip extensor torque is often used to rapidly accelerate the body upward and forward from a position of hip flexion (104). Brazil, Exell, Wilson, Willwacher, Bezodis and Irwin (19) reported that the hip joint was the largest generator of leg extensor energy in the front (61%) and rear (64%) during block push off. Moreover, Wiemann and Tidow (152) reported that a sprinter’s speed is directly related to the velocity of leg extension - a movement started from the highest point of the knee lift, down to foot contact and continued during the support phase. As training specificity can promote intermuscular coordination which has been shown to increase transference to sport performance (156), it would seem prudent to find training methods that specifically overload the hip musculature. WR is one type of training that directly addresses the concept of training specificity and therefore has been proposed as an optimal method to rotationally overload the hip joint during sprint running (73). Therefore, with WR thigh loading the rotational inertia of the thighs would increase, and thus it will take more muscular effort from the hip flexors, during the swing phase, and extensors, during the stance phase, to initiate and control the rotational movement of the thigh. That is, sprinting with thigh WR is essentially a resistance training exercise, though the exercise is expected to be highly specific as the athlete is sprinting.

Three studies have examined the effects of WR attached to the thigh musculature only, with loads ranging from 0.6-5.8% BM (80, 81, 94). However, no kinetics were collected, and the loads did not significantly change any kinematic variables of interest (stride length 0-0.3%, contact time 0-0.4% and flight time -1.1% to 3.2%). All three studies were completed at running speeds of 2.7-3.3 m/s on a treadmill, therefore over ground sprint-running has yet to be investigated. Moreover, the WR placement used in the three studies was approximately mid to upper thigh. Therefore, practitioners may be interested in understanding the effect of placing the WR more distal to the hip joint (i.e. distal aspect of the thigh) which increases the rotational inertia associated with moving and controlling the thigh. From the small body of WR research, it would seem there is limited kinematic and kinetic understanding of the use of thigh loaded WR, and furthermore, there are no training studies that have investigated the training effects of such loading. Given the evidence and limitations presented, thigh loaded WR would seem a method to rotationally overload the hip musculature and hence provide a means to improve sprint performance. Therefore, the purpose of this case study was to determine how distal thigh positioned WR of 2% BM affected sprint-running performance following a 5 week periodised training period.

8.2 Methods

8.2.1 Approach to the Problem

This research used a single subject case study design involving one male sprinter (32 years, 72.4 kg and 180.9 cm). The subject was a former national-level sprinter, who was actively engaged in sprint-based activities at the time of the study. Though the subject had not trained competitively for at least 3 years, he was engaged in different type of sprint activities, such as recreational soccer and touch rugby, and performing gym resistance training 2-3 times per week. The subject had the risks of the investigation explained prior to signing the informed consent form. All procedures and protocols were approved by the Auckland University of Technology Human Subject Ethics Committee. To determine the effects of thigh positioned WR on sprint-running performance, a 5 week, two to three times per week periodised training intervention was completed. Pre and post sprint 40 m sprint performance measures (sprint times at 10, 20, 30 and 40 m, sprint mechanical properties, kinematics and vertical stiffness) were visually analysed for trend, variability and change in level. In addition, the results were statistically analysed via the ±2 x SD band method (±2SD) (post mean above/below pre mean ±2SD) to identify substantial pre to post change.

8.2.2 Equipment

8.2.2.1 Radar

Instantaneous horizontal velocity data was collected (47 Hz) with a radar device (Stalker ATS II, Applied Concepts, Dallas, TX, USA) positioned directly behind the starting position at a distance of 5 m and at a vertical height of 1 m to approximately align with the participant's centre of mass (90). All data were collected using Stalker ATS system software (Model: Stalker ATS II Version 5.0.2.1, Applied Concepts, Dallas, TX, USA) supplied by the radar device manufacturer. The general mechanical ability to produce horizontal external force during sprint-running is portrayed by the linear force–velocity (F–v) relationship (34, 123). The mechanical capabilities of the lower limbs were characterised by the variables: V_0, F_0, and P_{max} (114). A custom-made LabVIEW program (Version 13.0, National Instruments Corp., Austin, TX, USA) was developed to calculate the variables based on the raw horizontal velocity data: V_0, F_0, P_{max}, and sprint split times (10. 20, 30 and 40 m). The methods of obtaining these variables have been validated in previous research during maximal sprint-running (87, 123). A high level of reliability (CV V_0 1.11% P_{max} 1.87%, F_0 2.93%) for inter-individual comparisons was found for each variable during over the ground sprint-running (123).

8.2.2.2 Inertial Measurement Unit

An IMU (IMeasureU Limited, Auckland) consisting of a 3-axis accelerometer, 3-axis gyroscope, and a 3-axis magnetometer was used to collect rotational kinematics from the left leg. Data were logged to the onboard memory of the IMU at 500 Hz for the duration of the trials, and then downloaded after each session for processing. The IMU was attached to the middle and lateral surface of the thigh, corresponding to the mid-point between the greater trochanter and lateral epicondyle of the femur, using elastic straps with tape placed onto the strap and leg to minimise movement. After reconstructing the data to two dimensional in the sagittal plane, thigh kinematic variables were calculated from the data using MATLAB (V2018a, Mathworks, Natick, Massachusetts, USA). Raw IMU data was trimmed to the length of each trial. Constraints were established to adjust for drift. The converted gyroscope data were then smoothed using a fourth-order, zero-lag, Butterworth digital filter with 100 Hz low pass filter. The recorded waveforms from the IMU for kinematics of the thigh were separated by steps by defining the maximum flexion and extension thigh range of motion to obtain angular displacement. Angular velocities were then determined based on the derivative of the distance (angle) with respect to time. Previous IMU studies found that root mean square error measures of shank angular displacement (≤ 5%) and velocity (≤ 10%), and trunk angular displacement (≤ 5%) were valid during sprinting (14, 23) with levels of reliability in trunk angular displacement (≤ 6%) also found (14). Twenty steps were recorded during the 40 m sprint, therefore, 10 steps from the left leg were analysed.

8.2.2.3 High-speed Video Camera

A high-speed video camera (Casio Exilim EX-F1, 300 frames per second) was positioned 12 m perpendicular to track, at a height of 1 m, to enable collection of kinematics between 30-40 m, corresponding to the maximum velocity phase. In order to assess the sprint-running kinematics of each subject, contact time, flight time and step frequency were calculated with the aid of computer software (Kinovea, 0.8.27). Ground contact times were calculated by counting the number of frames between touchdown and toe-off. Flight time was determined by counting the number of frames between toe-off and touchdown of the other leg. Step frequency was determined as inverse of the time between the touchdown of one leg and the touchdown of the other leg. Additionally, vertical stiffness was calculated using the spring mass model paradigm proposed by Morin, et al. (88). This method is based on force-time curve sine modelling, which allow calculations from simple mechanical parameters of flight and contact times, leg length, BM, and velocity. The data of the kinematic variables in each trial corresponds to the averaged of the last 10 m of the sprint.

8.2.3 Wearable Resistance

For the 5 week training study, the subject wore Lila™ Exogen™ compression shorts (Sportboleh Sdh Bhd, Kuala Lumpur, Malaysia) for each training session. WR totalling 2% BM (1.4 kg) was attached to the distal aspect of the thigh, therefore 1% BM (700 gram) was distally placed evenly around each thigh with 2/3 of the load attached predominately to the anterior and the remaining 1/3 posteriorly (Figure 16). WR of this magnitude was chosen to provide a comparable overload to other previously mentioned WR studies (13, 77, 78, 80, 81).

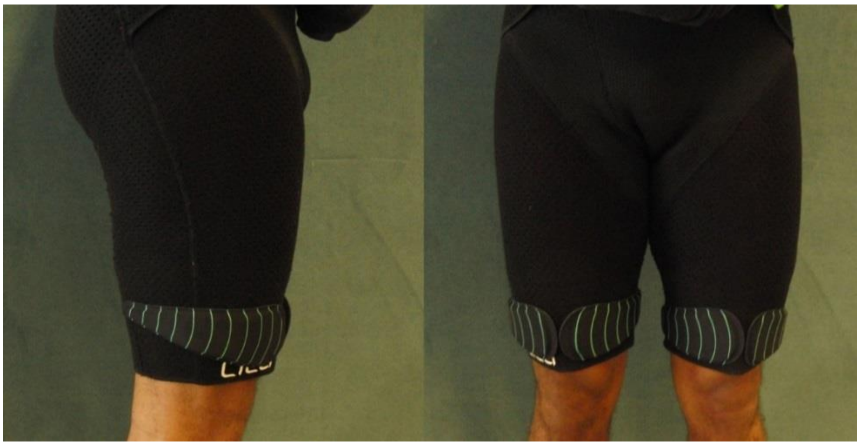

Figure 16. Wearable resistance of 1% body mass attached to the distal aspect of each thigh.

8.2.4 Testing Procedures

The subject was involved in two familiarisation sprint sessions, spread over two weeks prior to the first testing session to increase safeness and reliability of the 40 m sprint test. Pre-intervention anthropometric baseline data and pre and post intervention sprint performance baselines were established at the same time of day over three separate testing occasions that were separated by five days. Sprint performance was collected at the same time of day over the three separate occasions, for both pre and post testing.

8.2.5 Sprint Testing

For both pre and post-tests, the subject performed a standardised 30 minute warm-up that included light running, dynamic stretches, sprint technique drills and three 40 m sprints that progressively increased in intensity from 60% of maximal effort to 95% of maximal effort. The subject then performed two maximal effort 40 m sprints from a 3 point start position, separated with at least 6 minutes of passive rest between trials. The testing was conducted on an indoor track with athletic track surface.

8.2.6 Training Program

Throughout the duration of the study the subject was instructed to refrain from all other forms of sprint, resistance or cardiovascular training that may have influenced the results. During the 5 week intervention the subject was informed about hydration and nutritional requirements however, no specific dietary plans were given. All training sessions were supervised by a member of the research team. Details of the warm-up and training load are noted in Table 24. All training sessions, including the warm-up, were performed with the WR as shown in Figure 16.

Table 24. Wearable resistance of 2% body mass sprint training program over a 5 week period.

Week	Training Load	
1	2 sessions: Monday / Thursday	(3 x 40 m, Rest = 3 min)
2	3 sessions: Monday / Wednesday / Friday	(3 x 40 m, Rest = 4 min)
3	2 sessions: Monday / Thursday	(4 x 40 m, Rest = 5 min)
4	3 sessions: Monday / Wednesday / Friday	(4 x 40 m, Rest = 6 min)
5	2 sessions: Monday / Thursday	(3 x 40 m, Rest = 6 min)
Standardised warm-up	5 min jogging, 5 min active stretching and mobilisation, 20 min sprint technique drills, 3 x 40 m progressive sprints (60, 80, 95%) with 3 min rest between	

8.2.7 Statistical Analysis

To assess single case research, mixed statistical and visual analyses is the preferred method to determine change in longitudinal training intervention (66). The two band SD method (calculated by pre mean ± 2SD) was chosen due to its agreement to the C statistic and split method of trend estimation (106). When analysing and interpreting the data set, conclusions are based on ± 2SD graph observations (7). A substantial change is noted when post-test data points outside either band are found and these changes are further strengthened when consecutive or numerous data points fall outside the SD lines. In addition, the mean pre (mean of three data points) to post (mean of three data points) changes are provided (raw and % change). Thus, a statistical representation of change is quantified.

8.3 Results

8.3.1 Sprint Times

Substantially faster 10 m (-3.4%), 20 m (-2.5%), 30 m (-2.4%) and 40 m (-2.3%) times were found (Table 25). All three post 10 m, 30 m, and 40 m times were substantially faster and exceeded the ±2SD, while Post 1 and 3 were substantially faster at the 20 m mark (Figure 17).

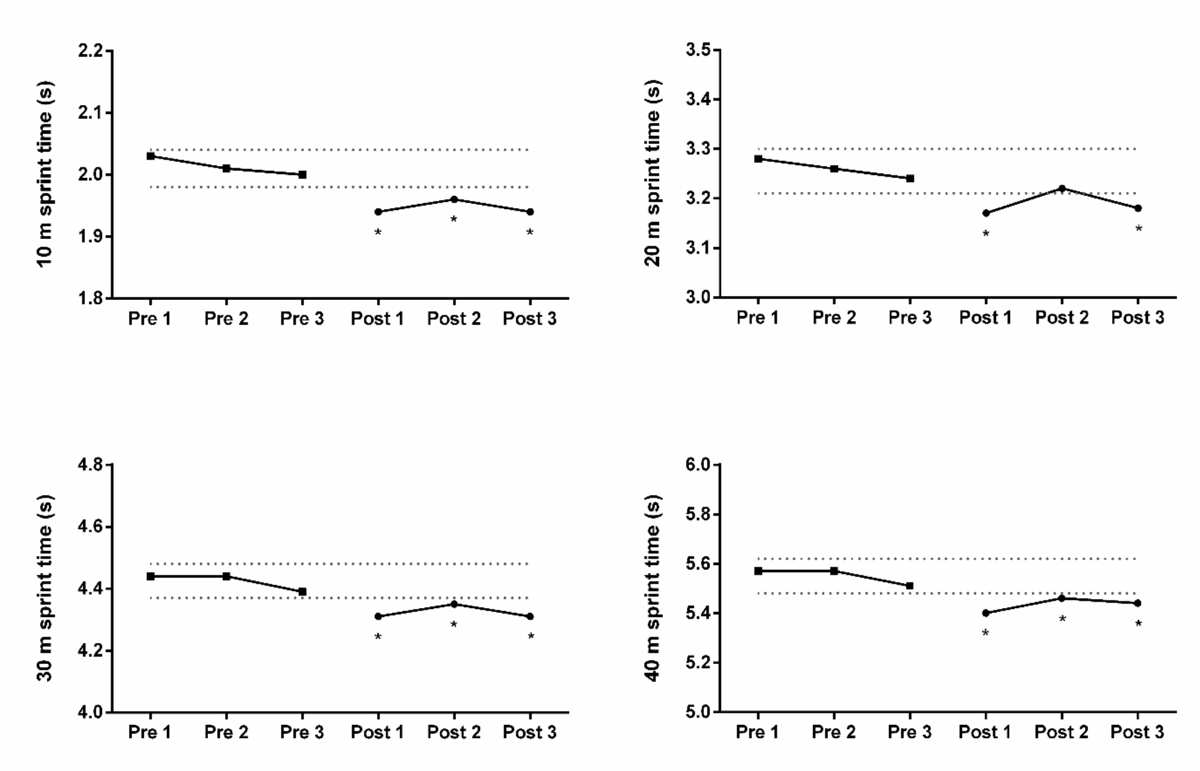

Figure 17. Changes in sprint times at 10, 20, 30 and 40 m. * = substantial changes

8.3.2 Sprint Mechanical Properties

Substantial increases were found in V_0 (1.2%), F_0 (7.1%) and P_{max} (8.4%) (Table 25). Measures of F_0 and P_{max} were found to show substantially greater changes and exceeded the ±2SD at Post 1 and 3, while V_0 exceeded the ±2SD at Post 1 (Figure 18).

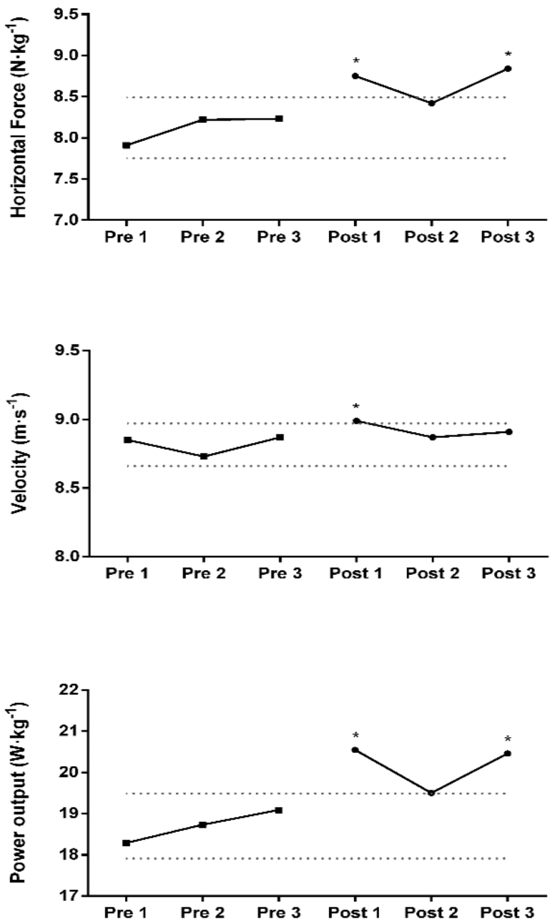

Figure 18. Changes in sprint mechanical properties. * = substantial changes

8.3.3 Kinematics and Vertical Stiffness

Contact times were substantially decreased (-5.5%), while flight times (4.7%) and vertical stiffness (12.9%) were substantially increased. Contact times and vertical stiffness exceeded the ±2SD in all post testing, while flight time exceeded the ±2SD in Post 3. No substantial changes were found in step frequency (0.5%), thigh angular displacement (-2.1%) and thigh angular velocity (4.5%) (Figure 19).

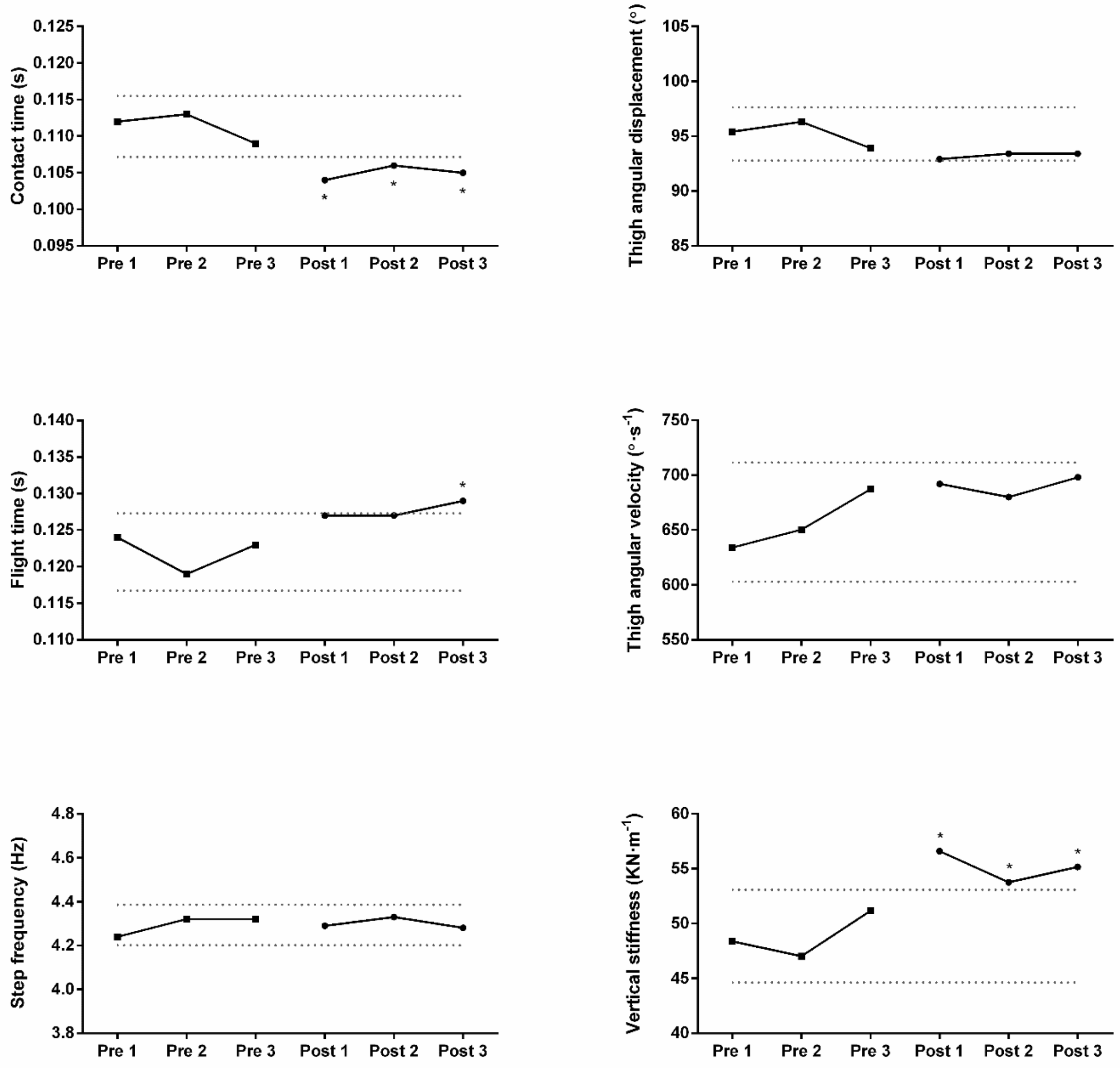

Figure 19. Changes in sprint kinematics and vertical stiffness. * = substantial changes

Table 25. Mean, standard deviation and % change sprint times, sprint mechanical properties, kinematics and vertical stiffness.

	PRE-Averaged	POST-Averaged	% Difference
Sprint times (s)			
10 m	2.02 ± 0.01	1.95 ± 0.01*	-3.4
20 m	3.26 ± 0.02	3.19 ± 0.03*	-2.5
30 m	4.43 ± 0.02	4.32 ± 0.02*	-2.4
40 m	5.56 ± 0.04	5.43 ± 0.03*	-2.3
Sprint mechanical properties			
V_0 (m/s)	8.80 ± 0.06	8.91 ± 0.07*	1.2
F_0 (N/kg)	8.09 ± 0.16	8.67 ± 0.22*	7.1
P_{max} (W/kg)	18.6 ± 0.27	20.2 ± 0.58*	8.4
Kinematics and vertical stiffness			
Contact time (s)	0.111 ± 0.003	0.105 ± 0.002*	-5.5
Flight time (s)	0.122 ± 0.004	0.128 ± 0.002*	4.7
Step frequency (Hz)	4.28 ± 0.04	4.30 ± 0.03	0.5
Thigh angular displacement (°)	95.2 ± 0.98	93.2 ± 0.23	-2.1
Thigh angular velocity (°/s)	657.12 ± 22.3	687.66 ± 13.5	4.5
Vertical stiffness (KN/m)	48.9 ± 2.11	55.2 ± 1.42*	12.9

* Changes of more than two standard deviation from baseline are deemed substantial

F_0 = theoretical maximum force; P_{max} = peak power production; V_0 = theoretical maximum velocity

8.4 Discussion

The purpose of this case study was to determine how thigh positioned WR of 2% BM affected sprint-running performance following a 5 week periodised training period. The main findings were: 1) substantially faster times were found at all distances over 40 m (-2.4% to -3.4%); 2) measures of V_0 (1.2), F_0 (7.1%) and P_{max} (8.4%) were substantially increased; 3) substantial changes in contact times (-5.5%), flight times (4.7%) and vertical stiffness (12.9%) were found; and, 4) step frequency, thigh angular displacement and velocity were not substantially changed. It appears that WR provides a sprint-specific method to achieve a rotational overload and subsequent speed specific adaptation enabling the athlete to improve sprint acceleration performance.

Previous leg WR over ground sprint-running studies found acute increases in relative maximal horizontal force of 5.4-6.2% with leg loading of 3% BM (77, 136). This is the first training sprint study with thigh attached WR that has found substantial increases in maximal horizontal force and power contributing to substantially faster velocity and sprint times at all split distances over 40 m.

As the ability to produce large amounts of horizontal force is a strong predictor of acceleration and sprint performance (89, 114), WR provides a training tool to improve these determinants of sprint acceleration performance. From previous acute WR studies, sprint times were only significantly decreased after 10 m, while from this training study, the greatest improvement in time was found at the 10 m mark. Therefore, thigh attached WR appears to improve the early acceleration phase of sprinting more than the later phases of the sprint. However, the effects of longer sprints (> 40 m) and with more elite sprinters may result in different findings and warrants future research.

Thigh rotational overload from the WR would be expected to affect the swing phase due the greater inertia overloading hip flexion, which concurrently affects step frequency. Thigh WR resulted in minimal disruption to thigh angular displacement, a 2° variability found between averaged pre and post results. Though thigh angular velocity was increased following the training program, the increases did not exceed the ±2SD level. However, a clear tendency to improve the velocity of the lower limbs can be seen, with an average increase of 4.5% between pre and post testing. According to the rotational component of Newton's second law of motion, the torque required to create angular acceleration is proportional to the moment of inertia of the object (the leg and mass), which is exponentially related to the radius from the axis (hip joint). Hence, as a load is placed more distally on the limb, the torque necessary to accelerate the limb will increase exponentially. As more torque is required during each step with the distal thigh placed WR, it would be expected that the leg muscles must generate more force, and thus produce more rotational mechanical work, for a given rate of limb movement when rotational displacement is maintained. Consequently, training with thigh WR resulted in an increased velocity of the lower limbs over similar displacement ranges. The importance of the hip musculature was noted by Dorn, et al. (43) who found that faster running speeds (>7.0 m/s) involved higher step frequencies, which were mainly produced by greater hip angular velocities in the swing phase. Therefore, from these factors, it could be expected that training with WR may have improved step frequency over the entire sprint, contributing to the faster times. However, as this study only measured kinematic data from the last 10 m (maximum velocity phase) and significant step frequency changes were not found, further research is required to verify this proposal.

Regarding the maximum velocity phase, substantially shorter contact times and longer flight times were found following the 5 week training period. Due to the shorter contact times, and the importance of this variable in calculating stiffness, vertical stiffness was substantially increased (12.9%). WR of 3% BM was shown to acutely reduce vertical stiffness (-6.2%) during 20 m sprint-running (77). However, training with the additional loading in this study may have overloaded the stretch shortening cycle causing a reduction of centre of mass displacement during the stance phase contributing to the improve sprint times. Moreover, vertical stiffness has been found to be related to sprint performance, as well as a differential factor between elite and average population groups (88, 102), highlighting the importance of this finding. As changes in these variables were only measured during the 30-40 m phase, further research is needed during the whole sprint distance. As flight time was increased it could be speculated that step length was increased, and therefore was the principle determinant of improved sprint times. However, a limitation of this study was that this variable was not measured. Moreover, only one subject completed the training program, therefore, further research is needed with a larger sample size and a control group performing the same training without WR.

8.5 Practical Applications

A 5 week WR sprint training program was an effective means to improve sprint performance over 40 m. Decreases in sprint times were accompanied by increases of sprint mechanical properties, reductions in contact times and increases in vertical stiffness. It seems, WR provides a sprint-specific method for rotational overload and subsequent speed specific adaptation. Practitioners may wish to utilise this form of placement for athletes needing to overload the acceleration and early maximal velocity phase of sprint-running. WR attached to the thigh enables a relevant load to be applied directly to the body that will directly stress specific sprint movements under the specific demands of an actual sport and competitive environment, without compromising the speed of motion, range of motion and specific skill. Future research is needed with a larger cohort to verify the findings in this case study. In addition, research is needed with different magnitudes of WR to assess adaptation in sprint performance metrics.

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

9.1 Summary

The overarching question of this thesis was “What are the rotational overload effects of thigh wearable resistance on kinematic and kinetic properties of sprint-running?” To answer this question, two areas were investigated: 1) What are the acute and longitudinal linear and rotational overload effects of thigh WR on kinematics and kinetics during sprint-running? and, 2) Can IMUs be used to quantify thigh rotational kinematics during sprint-running?

The basis for the overarching question was formulated and guided by gaps identified in the literature. Specifically: 1) a paucity of research had investigated acute and longitudinal linear effects of WR on sprint-running; 2) a magnitude of % BM loads had been used in sprint studies with a lack of understanding in WR load and placement yet to be determined; 3) no study had determined the kinematic and kinetic effects of distally placed WR during sprint-running and limited kinetic properties of sprinting had been investigated with WR; 4) no study had assessed changes in rotational kinematics or work with WR at sprinting speeds or during over ground sprint-running; 5) only one study had established the training effects of leg WR on sprint-running performance; and, 6) no study had quantified rotational kinematic measures of the thigh using IMUs at sprinting speeds. Therefore, addressing these gaps in the literature has provided the foundation for this thesis.

From Chapter 2 it was apparent that very little research had investigated the rotational effects of WR attached to the limbs. Moreover, though changes in linear kinematics and kinetics had been found with leg WR, an array of loading magnitudes had been used and the effects of distal loading were unknown in sprinting, therefore, a clear understanding of different loading schemes and placements of WR had yet to be established. The use of inertial sensors to quantify sprint performance metrics revealed mixed levels of reliability and validity due to differences in methodology (Chapter 3). Methods of attachment, sampling frequency and calibration were found to be important considerations for collection with sensors attached closer to the region being measured resulting in improved measurements. The ability to assess the rotational action of the limbs, and the effects of WR on the limbs rotational action, had received limited research, and only the reliability and validity of IMUs had been determined during treadmill running. Therefore, quantifying the rotational action of the limbs during over ground sprint-running required investigation.

From the findings in this Chapter 4, rotational kinematic measures of the thigh were able to be reliably quantified with an IMU attached to the thigh during sprint-running. Though measures of rotational kinematics were found to be underestimated compared to the referenced system, further collection of a greater number of steps may improve the accuracy of findings. This specific collection of rotational kinematics from an IMU enabled a measure of rotational work to be calculated and directly allows a more precise measure of individual thigh work during sprint-running. Thus, enabling the rotational effects of thigh WR to be quantified in subsequent chapters.

Understanding the load effects from thigh WR of 1, 2, and 3% BM on linear kinematics and kinetics and rotational kinematics was the focus of Chapter 5. Thigh WR of ≥2% BM resulted in moderate to large ES changes (-7% to -12%) in angular kinematics with trivial to small ES changes (-3.6% to 5%) found in linear kinematic and kinetic properties of NMT sprint-running. Therefore, given greater changes found with thigh WR ≥ 2% BM, the kinematic and kinetic effects of 2% BM on over ground sprint performance were investigated in Chapters 6 to 8. The linear kinematic and kinetic effects from thigh WR resulted in small ES increases (<2%) in sprint times, and moderate ES changes in net anterior-posterior impulses (-4.8%), vertical stiffness (-5.7%), and step frequency (-2.8%), though step length was unaffected (Chapter 6). The rotational changes were trivial to small ES increases in thigh angular displacement (0.6-3.4%), a significant decrease in thigh angular velocity (-2.5% to -8.0%), and rotational work was significantly increased (9.8-18.8%) (Chapter 7).

The placement of WR attached to the thighs enabled the rotational movement of lower limbs to be overloaded in a sprint-specific manner. Therefore, a more direct overload to the sprint action is achieved though thigh WR as seen by the greater changes to the rotational action of the thigh compared to the linear findings. From the acute changes to sprint performance, the thigh attached WR increases the rotational inertia of the leg with a concomitant decrease in angular velocity of the lower limbs and hence affects swing mechanics by reducing step frequency. These findings suggest that for athletes seeking to overload step frequency and develop vertical stiffness and anterior-posterior impulse during accelerated sprinting, WR enables the application of a sprint-specific form of rotational overloaded resistance training.

These acute findings are supported by the changes resulting from a 5 week WR sprint training program which was found to be an effective method to improve sprint performance over 40 m (Chapter 8). Substantial decreased sprint times were accompanied by increases of sprint mechanical properties. Specifically, training with thigh WR resulted in an increased angular velocity of the lower limbs over similar angular displacement ranges, emphasising the direct rotational overload and adaptation from the thigh WR. Moreover, linear changes in kinematics and kinetics were found with reduced contact times, and increased vertical stiffness, horizontal force and power contributing to substantially faster velocity. Therefore, WR provides a sprint-specific method for rotational overload and subsequent speed specific adaptation. Practitioners may wish to utilise this form of placement for athletes needing to overload the acceleration and early maximal velocity phase of sprint-running. Future research is needed to determine the effects over greater sprint distances.

9.2 Limitations

There are several limitations present within this current thesis:

- Due to ecological restrictions, the validity measures of rotational kinematics of the thigh during over ground sprint-running were only compared during 0-9 m and 41-50 m of a 50 m sprint, therefore, the validity between these distances and at greater than 50 m are unknown. Due to the high velocity attained during the 41-50 m section of the sprint, and the actual capture volume for the reconstruction is less than the camera set-up distance position, only one step was collected from the left leg, therefore, a greater number of steps may have resulted in improved validity measures in this phase.
- Analysis of rotational kinematics was examined in the sagittal plane only as this has been shown to be the plane were the greatest amount of work occurs. Therefore, the effects of thigh WR in other planes are unknown.
- IMUs are subject to errors, which can restrict the usefulness of the biomechanical assessment during sprints, therefore a sensor fusion of the accelerometer and gyroscope was used. A complementary filter was chosen over more advanced sensor fusion techniques such as Kalman filters for processing the IMU data, due to it being easier to implement and understand.
- Further analysis of different joint angles and torques could improve the understanding of the research area.
- As a single subject design was implemented for the longitudinal research, further research is needed with a larger sample size and a control group performing the same training without WR. In addition, research is needed with different magnitudes and placements of WR to assess long-term adaptation in sprint performance metrics.
- Though familiarisation sessions were used in Chapter 5-8, all participants included had no prior experience using WR, therefore, different outcomes may be expected with individuals that are more familiar to sprinting with WR.
- The participants in Chapters 6-8 were sprint based athletes, while the participants in Chapter 5 were recreationally trained subjects. Therefore, the acute and chronic effect of WR training may differ within individuals with a greater maximum velocity, better sprint mechanics, or other physical characteristics.
- Acute over ground sprint performance was measured up to 50 m, and longitudinal sprint performance measured up to 40 m, therefore, the effects of thigh WR on sprint performance beyond these distances are unknown.

9.3 Practical Applications

The following practical application can be considered:

- A wearable sensor attached to the thigh can be used to quantify rotational kinematics during sprint-running outside of a laboratory. This enables a more ecological valid method of assessing rotational limb kinematics and work during sprint-running performance.
- By utilising wearable sensor technology to quantify movement specific loading through WR, practitioners can assess sprint performance during sprint-specific resistance training. Thigh WR enables the rotational action of the thigh to be directly overloaded resulting in significant changes to rotational kinematics and linear kinematics and kinetics.
- Sprint-specific resistance training should be used to develop speed using thigh positioned WR. This form of resistance enables a relevant load to be applied directly to the body that will directly stress specific sprint movements under the specific demands of an actual sport and competitive environment, without compromising the speed of motion, range of motion and specific skill.
- WR offers athletes a means to target angular velocity of the thighs, step frequency, net anterior-posterior impulses, and vertical stiffness, during sprint specific form training, whilst minimally affecting step length. Given the importance of these variables in attaining sprinting speeds, and that the thigh moment inertia increases with WR, this form of loading could be a suitable training tool to overload the hip musculature to improve sprint mechanics.
- Substantial increases in maximal horizontal force and power suggest this form of loading may be suitable to improve acceleration and early maximal velocity phase of sprint-running.
- WR attached to the thighs can be used in a training plan to improve sprint times by increasing sprint mechanical properties, reducing contact times and increasing in vertical stiffness.

9.4 Future Research

The findings from this research have highlighted several considerations for future research:

- A greater number of steps at maximum velocity during over ground sprint-running should be collected to assess whether this improves validity measures from an IMU compared to a motion capture system.

- As IMU technology has improved over the past three years from data collection, improved sensors with onboard attitude and heading reference system systems are increasing in availability / popularity which could improve accuracy of angular calculations.
- Sprint training with lower body WR is a growing research area, hence as further training studies are completed, an improved knowledgebase can be developed. Future training studies should consider some of the previously mentioned limitations.
- As positive trends in performance were identified over a 5 week intervention, future studies should assess the impact of longer intervention.
- Testing diverse athlete groups, using crossover training studies and comparing factors that may be associated with responders and non-responders to WR interventions should provide a research focus. Furthermore, greater ranges of loading (> 2% BM) and placement positions should be compared and analysed.
- Sprint training with WR can improve sprint acceleration capabilities and lower limb stiffness. Though accelerated sprinting is essential for many sports, and lower limb stiffness is a determinant of maximal velocity sprinting, it is unknown whether adaptations to WR training transfer to maximal velocity sprinting beyond the distances of 40 m as tested in this thesis. Therefore, future research should examine the effects of WR on maximal velocity sprinting which would enhance the understanding of WR as a sprint training method.

9.5 Conclusions

This thesis provided original academic research into the effects of thigh WR on kinematic and kinetic properties of sprint-running and IMU utilisation to inform rotational workload changes. By utilising wearable sensor technology to investigate movement specific loading using WR, this thesis provided novel research which will be beneficial for practitioners in providing a more ecological valid measure of sprint performance during sprint-specific resistance training. Specifically, the previous unknown rotational effects from WR were found to be significantly changed with thigh WR and larger changes were found in rotational properties of sprint-running than the linear properties. Though future research is required to further elucidate the effectiveness of WR as a method to develop speed, incorporating WR as part of a comprehensive training program may supply a specific stimulus to overload the rotational work of the hip musculature, and also provide variability during sprint training.

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Appendices

Appendix I. Ethics Approval

Ethical Amendments to Ethics Application Number 15/07 for Data Collection for National Institute of Fitness, Kanoya, Japan

AUTEC Secretariat

Auckland University of Technology
D-88, WU406 Level 4 WU Building City Campus
T: +64 9 921 9999 ext. 8316
E: ethics@aut.ac.nz
www.aut.ac.nz/researchethics

12 October 2017

John Cronin
Faculty of Health and Environmental Sciences
Dear John

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

Thank you for your request for approval of amendments to your ethics application.

The amendment to the recruitment and data collection protocols is approved.

I remind you of the Standard Conditions of Approval.

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

Non-Standard Conditions of Approval

1. Provision of the Japanese translations.

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

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

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

Yours sincerely,

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

Cc: Jono Neville; ksimperingham@gmail.com

Ethical Amendment to Ethics Application Number 15/07 for Data Collection for New Zealand

AUTEC Secretariat

Auckland University of Technology
D-88, WU406 Level 4 WU Building City Campus
T: +64 9 921 9999 ext. 8316
E: ethics@aut.ac.nz
www.aut.ac.nz/researchethics

20 February 2018

John Cronin
Faculty of Health and Environmental Sciences
Dear John

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

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

The amendment to the recruitment protocols is approved.

I remind you of the Standard Conditions of Approval.

1. A progress report is due annually on the anniversary of the approval date, using form EA2, which is available online through http://www.aut.ac.nz/researchethics.
2. A final report is due at the expiration of the approval period, or, upon completion of project, using form EA3, which is available online through http://www.aut.ac.nz/researchethics.
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For any enquiries please contact ethics@aut.ac.nz

Yours sincerely,

K O'Connor

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

Cc: ksimperingham@gmail.com

AUTEC Secretariat

Auckland University of Technology
D-88, WU406 Level 4 WU Building City Campus
T: +64 9 921 9999 ext. 8316
E: ethics@aut.ac.nz
www.aut.ac.nz/researchethics

4 February 2019

John Cronin
Faculty of Health and Environmental Sciences

Dear John

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

Thank you for your request for approval of an extension to your ethics application. An extension until 14th April 2020 is approved.

I remind you of the **Standard Conditions of Approval**.

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

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

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

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

Yours sincerely,

Kate O'Connor
Executive Manager
Auckland University of Technology Ethics Committee
Cc: ksimperingham@gmail.com

Appendix II. Participant Information Sheets, Medical Questionnaires and Consent Forms

Data Collection for National Institute of Fitness, Kanoya, Japan

Participant Information Sheet

Date Information Sheet Produced:

18 October 2017

Project Title

Light Variable Resistance Training™ with Exogen™ Exoskeletons

An Invitation

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

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

What is the purpose of this research?

The purpose of this research is to analyse the changes in typical sporting movements (e.g. jumping, running, sprinting and cycling) that occur when small amounts of external loading are attached to the body. Exogen™ exoskeletons include shorts, sleeveless tops and upper arm, forearm and calf sleeves to which small (approximately 19 cm long) loads of 50 – 200 g can be attached with Velcro. This research will quantify the acute changes in typical sporting movements that occur when loads are attached to various sites around the body (e.g. upper vs. lower body and centrally located loading vs. loading positioned towards the extremities of the limbs). The research findings will be reported as conference presentation(s) and scientific journal article(s).

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

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

What will happen in this research?

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

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

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

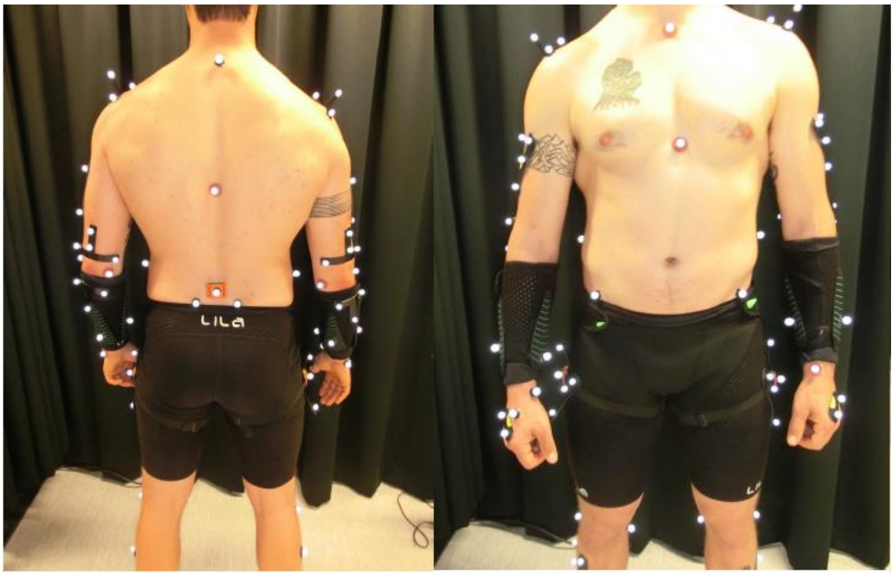

Figure 2. Attachment sites of retro-reflective markers for upper limb loading

What are the discomforts and risks?

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

How will these discomforts and risks be alleviated?

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

What are the benefits?

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

What compensation is available for injury or negligence?

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

How will my privacy be protected?

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

What are the costs of participating in this research?

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

What opportunity do I have to consider this invitation?

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

How do I agree to participate in this research?

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

Will I receive feedback on the results of this research?

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

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

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

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

Whom do I contact for further information about this research?

Researcher Contact Details:

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

Project Supervisor Contact Details:

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

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

Consent Form

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

Project Supervisor: **Professor John Cronin**

Researcher: **Paul Macadam**

○ I have read and understood the information provided about this research project in the Information Sheet dated 18 October 2017.

○ I have had an opportunity to ask questions and to have them answered.

○ I understand that I may withdraw myself or any information that I have provided for this project at any time prior to completion of data collection, without being disadvantaged in any way.

○ I am not suffering from heart disease, high blood pressure, any respiratory condition (mild asthma excluded), any illness or injury that impairs my physical performance.

○ I agree to take part in this research.

○ I agree that my test results may be provided to my sports coach, manager or doctor.

Yes○ No○

○ I agree to my test results being stored in de-identified form (without my name or personal details attached) in the SPRINZ research database and potentially used in future research studies of a similar nature:

Yes○ No○

○ I wish to receive a copy of the report from the research (please tick one):

Yes○ No○

Participant's signature:

....……………………………………………………………

Participant's name:

....……………………………………………………………

Participant's Contact Details (if appropriate):

………………………………………………………………………………………..

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Date:

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

Medical Questionnaire

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

Project Supervisor: **Professor John Cronin**

Researcher: **Paul Macadam**

First Name: ___________________________________

Last Name: ___________________________________

Email: _______________________________________

Phone: ______________________________________

Date of Birth: _____ / _____ / ________ *day / month / year*

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

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

____

____

____

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

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

____

____

____

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

Participant's signature:...

Date: ....

Translated Participant Information Sheet and Consent Forms into Japanese

別紙1

研究参加者各位

鹿屋体育大学
特任助教永原隆

研究の概要と被検者の有する権利について

1. 研究の名称
「下肢に付加したウェアラブルレジスタンス用具が疾走に及ぼす影響の検証および慣性センサによる疾走評価の妥当性検証」

2. 研究実施期間
承認日ー平成31年3月31日

3. 研究実施場所
3.1所在地：鹿児島県鹿屋市白水町 1 番地
3.2名称：鹿屋体育大学スポーツパフォーマンス研究棟
3.3連絡先：鹿屋体育大学特任助教永原隆
鹿児島県鹿屋市白水町 1 番地
Phone: 0994-46-5034 Fax : 0994-46-5030
E-mail: nagahara@nifs-k.ac.jp

4. 研究総括責任者
4.1 氏名 ：永原隆
4.2 所属機関・部局・役職：
鹿屋体育大学特任助教
連絡先：鹿屋体育大学特任助教永原隆
鹿児島県鹿屋市白水町 1 番地
Phone: 0994-46-5034 Fax : 0994-46-5030
E-mail: nagahara@nifs-k.ac.jp

5. 研究総括責任者以外の研究者と役割
Prof. John Cronin (Auckland University of Technology)：研究の立案，論文の執筆
6.研究の目的
短距離走では，疾走中に下肢を前後に素早く動かすために，股関節や膝関節における大きな屈曲伸展トルクの発揮が，そのパフォーマンス向上に不可欠です．近年，タイツに薄い板状の錘を付加するウェアラブルレジスタンス（WR）用具が販売され，疾走における股関節や膝関節の屈曲伸展筋力の向上を目的としたトレーニングに用いられています．WR用具は，下肢や上肢，体幹部にタイツ様の衣類を着用し，マジックテープで任意の重さの錘を付加す

ることで，実際のスポーツにおける運動動作に必要な筋力を向上させるレジスタンストレーニングに用いられています．このようなWR用具を用いたトレーニングによって，疾走能力の向上が期待されていますが，錘の付加によって疾走動作が大きく変わってしまう危険性があります．錘の付加によって疾走動作が変わってしまう場合，疾走の技術面に悪影響を及ぼすことが想定されます．しかし，錘の付加によって疾走動作が変化するのか，またその程度については明らかになっていません．
一方，近年の科学技術の進歩により，小型で安価な慣性センサが販売されており，それを用いた疾走の評価が試みられています．慣性センサによって適切に疾走を評価することができれば，測定場所の制約を受けることがなくなり，測定データを活用したエビデンスベースのトレーニングが可能になります．しかし，慣性センサを用いた疾走の評価の妥当性については，これまで検証されていません．
本研究では，スタート直後の加速疾走，一定速度での疾走を対象に異なる努力度条件においてWR用具が疾走に及ぼす影響をキネマティクス，キネティクスの観点から明らかにするとともに，慣性センサによる疾走のキネマティクス，キネティクス分析の妥当性について検証することを目的とします．

7. 研究の概要
本研究では，以下に示す4つの実験を行い，得られたデータを分析することでWR用具が疾走に及ぼす影響を検討し，慣性センサによる疾走評価の妥当性を検証します．

（1）最大下での定速疾走実験
最大努力の60%（2回），75%（2回），90%（1回）での一定速度走行を陸上競技の短距離・跳躍選手に行わせ，その際の疾走動作，地面反力，慣性データをモーションキャプチャシステム，フォースプレート，慣性センサによって計測します．錘の条件は，無負荷，各脚400g，各脚800gとし，WR用具は大腿部遠位に装着します（試技数合計，15回）．

（2）最大速度疾走実験
最大努力での一定速度走行を陸上競技の短距離・跳躍選手に行わせ，その際の疾走動作，地面反力，慣性データをモーションキャプチャシステム，フォースプレート，慣性センサによって計測します．錘の条件は，無負荷，各脚400g，各脚800gとし，WR用具は大腿部遠位に装着します（試技数合計，6回）．

（3）最大下での加速疾走実験
最大努力の50%（2回），75%（2回），90%（1回）での加速疾走（15m）を陸上競技の短距離・跳躍選手に行わせ，その際の疾走動作，地面反力，慣性データをモーションキャプチャシステム，フォースプレート，慣性センサによって計測します．錘の条件は，無負荷，各脚200g，各脚400gとし，WR用具は下腿部遠位に装着します（試技数合計，15回）．
（4）最大加速疾走実験
最大努力での加速疾走（15m）を陸上競技の短距離・跳躍選手に行わせ，その際の疾走動作，地面反力，慣性データをモーションキャプチャシステム，フォースプレート，慣性センサによって計測します．錘の条件は，無負荷，各脚200g，各脚400gとし，WR用具は下腿部遠位に装着します（試技数合計，6回）．

8.被検者に関する事項
8.1想定される被検者に与える影響
本研究において実施する測定では，被検者には全力もしくはそれに近い状態での試技を要求します．それゆえ，被検者の体調不良，実験試技に伴う疲労や脱水，ウオーミングアップの

不足等により，障害や気分が悪くなる事態が発生する恐れがあります．特に，最大努力での疾走試技では，ウオーミングアップの不足，体調の不良，実験に伴う疲労等により，下肢の筋肉や関節の障害が発生する危険性があります．

8.2被検者への影響を軽減させるための対策
本研究において実施する測定は，いずれも非侵襲的な測定方法を用いて実施します．それらの安全性は高く，国際的にも広く活用されているものです．しかし，本研究実施中，8.1に示したような参加者への影響が想定されます．参加者の安全性を確保し，事故の発生を未然に防ぐため，以下の点について研究全体を通して基本方策とします．
１）測定開始前に被検者の体調チェックを行い，何らかの異常や痛みがある場合には，測定は実施しません．
２）測定前の準備運動段階，あるいは測定実施中に，被検者に何らかの不調が生じた場合，またその兆候が認められた場合には直ちに測定を中止します．被検者を安静な状態に戻し，必要に応じて速やかに救急医療機関に連絡をとり，適切な処置を受けられるように配慮します．
３）最大努力での疾走を実施する前には，被検者の体調の確認をするとともに，被検者の方には測定実施前にストレッチング，準備運動を入念に行っていただきます．また，測定前に軽い筋力発揮や課題動作を数回行い，測定の手順に慣れていただきます．
４）測定において被検者が使用する用具および測定フィールドとなる走路について，予め入念にチェックし，不具合がないかどうかを確認し，不具合が見つかった場合には適切に処置します．
５）測定中に何らかの障害が生じた場合には，実験をただちに中止し，被検者を安静な状態に戻すと同時に，必要に応じて医療機関に連絡し，被検者を搬送し適切な処置が受けられるようにします．

8.3参加者の人権擁護のための配慮
（１） 測定に際しては，参加者に研究の目的，方法，安全性などに関して十分な説明を行った上で，同意を得て実施します．
（２）参加者は，研究の目的，方法及びその他の事項について，いつでも研究実施者に対して質問し，十分な回答を得る権利を有します．
（３）参加者は，研究への協力を同意した後でも，また実際に協力している間においても同意を撤回し，また協力を中止する権利を有します．
（４）研究の過程において，参加者に対して質問がなされる場合には，参加者はそれらの質問の一部または全部に対する回答を拒否する権利を有します．
（５）研究の過程におけるデータの保存及び研究成果の発表にあたっては，被検者のプライバシーを尊重し，他者に参加者個人を特定できないように配慮します．また，参加者個人へのデータや情報の親展性が保証されるようにします．
（６）実験風景を含む写真撮影など個人の肖像権に関することは，その個人に了解を得たうえで実施します．
（７）測定に要する時間以外の生活時間帯は一切拘束しません．

8.4参加者の募集
参加者はボランティアとし，研究内容の詳細及び受けるかもしれないリスクについて十分な説明を行います．そのうえで，実験参加希望者に研究参加同意書（別紙2）を手渡します．
その後，日を改めて実験参加に同意する希望者から本人の自筆サインのある研究参加同意書を受け取ります．研究参加同意書を提出した被検者候補者の健康状況，障害の有無等を確認した後，被検者としてご協力いただくかどうかの最終決定を行います．ご本人の意志で，被

検者として実験に参加していただくことを決定していただいた方には，実験参加に対する最終同意の確認を取らせていただきます.

9. 実験装置の安全管理と運用体制
使用する実験装置は，各研究者が日常の研究活動で使用し，使用手順を熟知しているものに限ります．また，実験に使用するすべての装置・用具は，験開始前に十分な保守・点検を済ませ，本測定に支障がないように万全を期します.

10. 緊急時の医療体制
実験中に被検者に緊急事態が発生した場合には，応急処置を行うと同時に，必要であれば医療機関に連絡し，その被検者を搬送し適切な処置が受けられるように配慮します.

研究参加同意書

(研究責任者の所属・職・氏名）

鹿屋体育大学

特任助教永原隆殿

（研究課題名）

「下肢に付加したウェアラブルレジスタンス用具が疾走に及ぼす影響の検証および慣性センサによる疾走評価の妥当性検証」

私は，上記の研究課題の研究内容について適切かつ十分な説明を受け，その目的・被検者の人権擁護・研究の安全性等を良く理解しましたので，この研究に被検者として参加することに同意致します.

氏名：

住所：

電話番号：

（日付）平成年月日

説明責任者：永原隆

Data Collection for New Zealand

Acute Data Collection

Participant Information Sheet

Date Information Sheet Produced:

1 February 2018

Project Title

Light Variable Resistance Training™ with Exogen™ Exoskeletons

An Invitation

My name is Paul Macadam and I am a PhD student at SPRINZ (Sports Performance Research Institute New Zealand) at the AUT Millennium Campus of the Auckland University of Technology (AUT), New Zealand. We are currently conducting a study into the effect on sporting movements of added external weight using a new product called an Exogen™ exoskeleton (*see Figure 1 below*). Your participation in this study would be greatly valued but is entirely voluntary and you may withdraw at any time prior to the completion of the data collection. Lila™, the producer of Exogen™, will provide Exogen™ suits for use during testing and may provide some grants (e.g. student scholarships) to help fund the research project. The results from the studies will be provided in de-identified form (i.e. without your associated name and personal details) to Lila™ in the form of journal or thesis publications and/or conference presentations. Your consent to participate in this research will be indicated by your signing and dating the consent form. Signing the consent form indicates that you have read and understood this information sheet, freely give your consent to participate, and that there has been no coercion or inducement to participate.

Figure 1. Exogen™ exoskeletons

What is the purpose of this research?

The purpose of this research is to analyse the changes in sprint performance that occur when small amounts of external loading are attached to the body. Exogen™ exoskeletons include shorts, sleeveless tops and upper arm, forearm and calf sleeves to which small (approximately 19 cm long) loads of 50 – 200 g can be attached with Velcro. This research will quantify changes in non-motorised treadmill sprinting that occur when loads are attached to the legs. The research findings will be reported as conference presentation(s) and scientific journal article(s).

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

Participants are required to be healthy, injury-free recreationally- or competitively-active males or females, aged 18-35 years old. You have been identified as a suitable participant for this project so we would like to invite you to participate.

What will happen in this research?

If you choose to participate in this project, you will be required to complete three testing session at AUT Millennium Campus for approximately one to two hours per session.

Following the standardised 10 minute warm-up you will complete a series of 10 second sprints on a non-motorised treadmill with and without Exogen loading attached to the thigh. In addition, sprints will be performed with inertial measurement units (IMU) attached via strapping to the thighs (Figure 3).

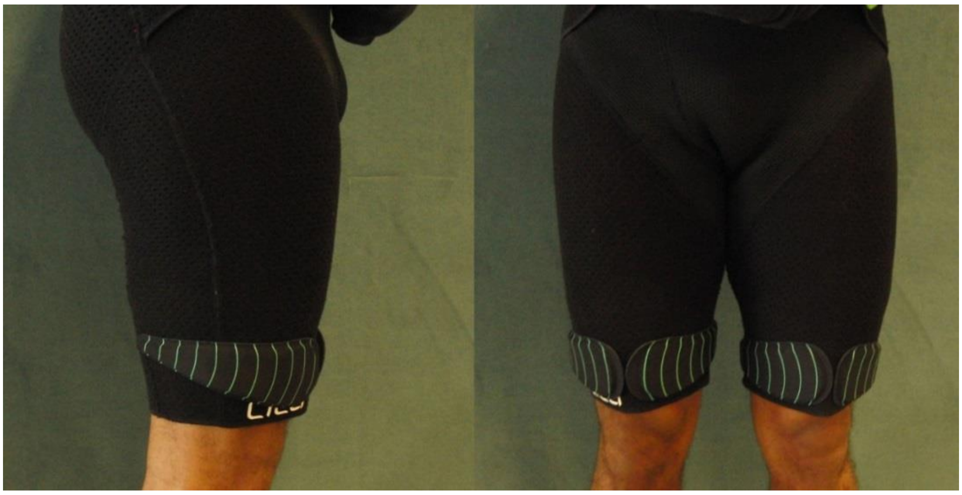

Figure 2. Exogen shorts with thigh loading of 2% body mass

Figure 3. Inertial measurement unit with strapping

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.

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 area of speed 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, AUT Millennium, will be the first point of contact to deal with any incidents.

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 approximately 3 x 1-2 hours for testing.

What opportunity do I have to consider this invitation?

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

How do I agree to participate in this research?

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

Will I receive feedback on the results of this research?

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

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

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

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

Whom do I contact for further information about this research?

Researcher Contact Details:

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

Project Supervisor Contact Details:

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

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

Single Subject Training Study Data Collection

Participant Information Sheet

Date Information Sheet Produced:

1 February 2019

Project Title

Light Variable Resistance Training™ with Exogen™ Exoskeletons

An Invitation

My name is Paul Macadam and I am a PhD student at SPRINZ (Sports Performance Research Institute New Zealand) at the AUT Millennium Campus of the Auckland University of Technology (AUT), New Zealand. We are currently conducting a study into the effect on sporting movements of added external weight using a new product called an Exogen™ exoskeleton (*see Figure 1 below*). Your participation in this study would be greatly valued but is entirely voluntary and you may withdraw at any time prior to the completion of the data collection. Lila™, the producer of Exogen™, will provide Exogen™ suits for use during testing and may provide some grants (e.g. student scholarships) to help fund the research project. The results from the studies will be provided in de-identified form (i.e. without your associated name and personal details) to Lila™ in the form of journal or thesis publications and/or conference presentations. Your consent to participate in this research will be indicated by your signing and dating the consent form. Signing the consent form indicates that you have read and understood this information sheet, freely give your consent to participate, and that there has been no coercion or inducement to participate.

Figure 1. Exogen™ exoskeletons

What is the purpose of this research?

The purpose of this research is to analyse the changes in sprint performance that occur when small amounts of external loading are attached to the body. Exogen™ exoskeletons include shorts, sleeveless tops and upper arm, forearm and calf sleeves to which small (approximately 19 cm long) loads of 50 – 200 g can be attached with Velcro. This research will quantify changes in over ground sprinting that occur when loads are attached to the legs. The research findings will be reported as conference presentation(s) and scientific journal article(s).

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

Participants are required to be healthy, injury-free recreationally- or competitively-active males aged 18-35 years old. You have been identified as a suitable participant for this project so we would like to invite you to participate.

What will happen in this research?

If you choose to participate in this project, you will be required to complete two testing session at AUT Millennium Campus for approximately one to two hours per session and complete a 5 week sprint training program.

Training plan

You will complete a 5 week sprint training program with wearable resistance of 2% body mass attached to the thigh (Figure 2).The sprint training sessions will be completed two or three times weekly (separated by ≥ 48 hours) and will last approximately 1 hour each session. Each training session will begin with a 20 minute warm-up where you will perform dynamic stretches, sprint specific warm up exercises, and various footwork and agility drills. After warm-up, a series of sprints will be performed which will vary in distance and repetition during the 5 week training plan.

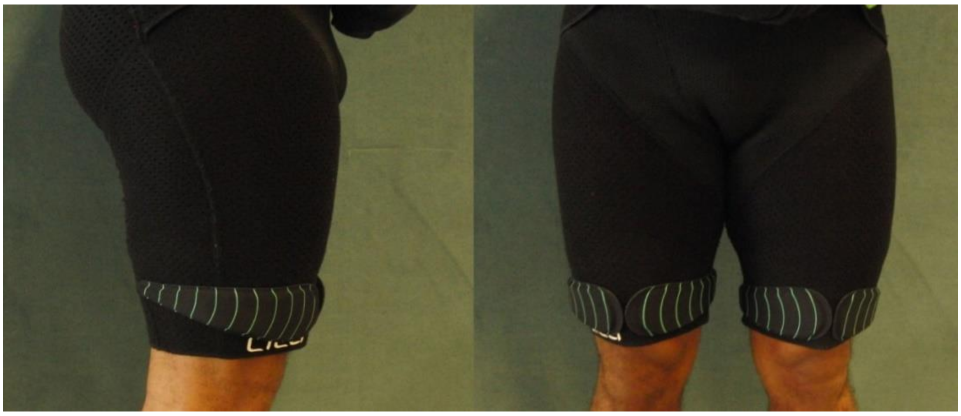

Figure 2. Exogen shorts with thigh loading of 2% body mass

Testing session

One week before and one week following the training program you will perform three testing sessions which will last 1-2 hours. Following a standardised 10-15 minute warm-up you will complete two maximal effort sprints of 50 m on an indoor rubberised artificial athletics track with inertial measurement units attached via a strap to the thigh (Figure 3) to collect measures of rotational workload. Anthropometrical measurements will also be collected at each session.

Figure 3. Inertial measurement unit with strapping

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.

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 area of speed 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, AUT Millennium, will be the first point of contact to deal with any incidents.

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 approximately 2 x 1-2 hours for testing, and 10 x 1 hour per session for the training program.

What opportunity do I have to consider this invitation?

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

How do I agree to participate in this research?

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

Will I receive feedback on the results of this research?

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

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

Any concerns regarding the nature of this project should be notified in the first instance to the Project Supervisor, John Cronin, john.cronin@aut.ac.nz, 0064 921 9999 ext 7523.
Concerns regarding the conduct of the research should be notified to the Executive Secretary of AUTEC, Kate O'Connor, ethics@aut.ac.nz, 0064 921 9999 ext 6038.

Whom do I contact for further information about this research?

Researcher Contact Details:

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

Project Supervisor Contact Details:

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

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

Consent Form

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

Project Supervisor: **Professor John Cronin**

Researcher: **Paul Macadam**

○ I have read and understood the information provided about this research project in the Information Sheet dated 1 February 2019.

○ I have had an opportunity to ask questions and to have them answered.

○ I understand that I may withdraw myself or any information that I have provided for this project at any time prior to completion of data collection, without being disadvantaged in any way.

○ I am not suffering from heart disease, high blood pressure, any respiratory condition (mild asthma excluded), any illness or injury that impairs my physical performance.

○ I agree to take part in this research.

○ I agree that my test results may be provided to my sports coach, manager or doctor.

Yes○ No○

○ I agree to my test results being stored in de-identified form (without my name or personal details attached) in the SPRINZ research database and potentially used in future research studies of a similar nature:

Yes○ No○

○ I wish to receive a copy of the report from the research (please tick one):

Yes○ No○

Participant's signature:

....……………………………………………………………

Participant's name:

....……………………………………………………………

Participant's Contact Details (if appropriate):

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Date:

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

Medical Questionnaire

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

Project Supervisor: **Professor John Cronin**

Researcher: **Paul Macadam**

First Name: ______________________________________

Last Name: ______________________________________

Email: ____

Phone: ____

Date of Birth: _____ / _____ / ________ *day / month / year*

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

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

____

____

____

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

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

____

____

____

☐ I have read and understood the information provided about this research project in the Information Sheet dated 1 February 2019.

☐ I understand that I may withdraw myself or any information that I have provided for this project at any time prior to completion of data collection, without being disadvantaged in any way.

☐ I have answered the questions and provide the required information above to the best of my ability.

☐ I agree to take part in this research.

Participant's signature:...

Date: ....

Appendix III. Abstracts of Chapters as Published, in Press, or in Review

Chapter 2.

Macadam, P., Cronin, J.B, Uthoff, A.M., Feser, E. (2019). The effects of different wearable resistance placements on sprint-running performance: a review and practical applications. Strength and Conditioning Journal, 41 (3), 79-96. doi: 10.1519/SSC.0000000000000444.

Abstract (87 words)

Wearable resistance (WR) provides the practitioner with the means to overload sprinting in a movement specific manner. This article investigates the effects of WR on sprint-running performance by discussing the mechanisms associated with WR, as well as those factors that must be taken into consideration by the practitioner when they wish to implement a program that utilises WR. In particular, the effects of different WR body placements (trunk, legs and arms), will be discussed. Practical applications and conclusions from the analysis will be provided for the practitioner.

Chapter 3.

Macadam, P., Cronin, J.B, Diewald, S., Neville, J. (2019). Quantification of the validity and reliability of sprint performance metrics computed using inertial sensors: a systematic review. Gait & Posture Journal, 73, 26-38. doi: 10.1016/j.gaitpost.2019.07.123.

Abstract (274 words)

Background: Wearable inertial sensors enable sprinting to be biomechanically evaluated in a simple and time efficient manner outside of a laboratory setting.

Research Question: Are wearable inertial sensors a valid and reliable method for collecting and measuring sprint performance variables compared to referenced systems?

Methods: PubMed, SPORTDiscus, and Web of Science were searched using the Boolean phrases: ((run* OR sprinting OR sprint*) AND (IMU OR inertial sensor OR wearable sensor OR accelerometer OR gyroscope) AND (valid* OR reliabil*)). Articles with injury-free subjects of any age, sex or activity level were included.

Results: Fifteen studies met the inclusion criteria and were retained for analysis. In summary, higher Intraclass correlation [ICC] or Pearson correlation coefficients (r) were observed for contact time (ICC ≥ 0.80, r ≥ 0.99), trunk angular displacement (r ≥ 0.99), vertical and horizontal force (ICC ≥ 0.88), and theoretical measures of force, velocity and power (r ≥ 0.81). Low coefficient of variation (CV) were found in peak velocity (≤ 1%), average velocity (≤ 3%), and contact time (≤ 3%,). Average and peak velocity, and resultant forces, were found to have a wide range of r (0.32-0.92) and CVs (0.78-20.2%). The lowest r (-0.24 to 0.49) and highest CVs (15-22.4%) were noted for average acceleration, crania-caudal force, instantaneous forces, medio-lateral ground reaction forces, and rate of decrease in ratio of forces.

Significance: Due to a wide range of methodological differences, a clear understanding of the validity and reliability of different inertial sensors for the analysis of sprinting has yet to be established. Future research into the sensor's placement, attachment method and sampling frequency are among several factors that need further investigation.

Chapter 4.

Macadam, P., Cronin, J.B., Nagahara, R., Wells, D., Uthoff, A., Graham, S., Diewald, S., Tinwala, F., Kameda, M., Neville, J. Can inertial measurement units quantity thigh rotational kinematics during sprint-running? Measurement in Physical Education and Exercise Science. (In review).

Abstract (148 words)

This study investigated the capability of an inertial measurement unit (IMU) for quantifying rotational kinematics during 50 m sprint-running. Fourteen male participants completed two maximum effort sprints with an IMU attached to their left thigh. The IMU derived thigh angular displacement and velocity were reproducible between trials (change in the mean 1-1.5%, coefficient of variation 6.7-9.7%, intraclass correlation coefficient [ICC]: 0.95-0.96). Compared to the motion capture system measures, the IMU was found to underestimate thigh angular displacement (relative error -6.7 to -9.0%, bias 7.5-10.4º, ICC 0.79-0.84) and angular velocity (relative error -5.3 to -16.4%, bias 35.7-146$^{o}\cdot s^{-1}$, ICC 0.45-0.64). IMU measures of thigh angular displacement and velocity were reproducible between trials, although the validity of the IMU remains unclear. The IMU has potential to provide an in-field measure of rotational kinematics with further research needing to investigate a greater number of steps required to determine the utility of this device.

Chapter 5.

Macadam, P., Nuell, S., Cronin, J.B., Nagahara, R., Diewald, S., Forster, J., Fosch, P. Load effects of thigh wearable resistance on angular and linear kinematics and kinetics during non-motorised treadmill sprint-running. European Journal of Sport Science. doi: 10.1080/17461391.2020.1764629

Abstract (244 words)

The aim of this study was to investigate the load effects of thigh attached wearable resistance (WR) on linear and angular kinematics and linear kinetics during sprint-running. Fourteen recreational active subjects performed a series of sprints with and without WR of 1, 2, and 3% body mass (BM) in a randomised order. Sprints were performed on a non-motorised treadmill which collected velocity, and linear step kinematics and kinetics. Angular kinematics of the thigh were collected from an inertial measurement unit attached to the left thigh. Trivial decreases were found in velocity with all WR loads (-0.9 to -.2.4%, effect size [ES] 0.09-0.17, $p > 0.05$). The WR conditions resulted in significantly decreased average step frequency (-2.0% to -3.0%, ES 0.35-0.44, $p < 0.05$) with loads of ≥ 2% BM, whereas average step length was statistically unchanged (1.9-2.8%, ES 0.20-0.33). Average angular displacement was significantly decreased (-7.0% to -10.3%, ES 0.88-1.10, p 0.00-0.03) with loads of ≥ 2% BM. Average angular flexion velocity (-10.2%, ES 1.07, p 0.02) and extension velocity (-12.0%, ES 0.85, p 0.01) were significantly decreased with 3% BM. Trivial to small ES changes ($p > 0.05$) were found in the kinetic measures of interest. Thigh WR provides a sprint-specific rotational overload resulting in greater changes to angular kinematics than linear properties of sprint-running. For practitioners who wish to target thigh angular kinematics and step frequency without decreasing step length, thigh WR of ≥ 2% BM offers a sprint-specific resistance training tool.

Chapter 6.

Macadam, P., Nuell, S., Cronin, J.B., Nagahara, R., Uthoff, A.M., Tinwala, T., Graham, S., Neville, J. (2019). Thigh positioned wearable resistance affects step frequency not step length during 50 m sprint-running. European Journal of Sport Science. doi: 10.1080/17461391.2019.1641557.

Abstract (239 words)

This study determined the acute changes in spatio-temporal and impulse variables when wearable resistance (WR) of 2% body mass was attached distally to the thighs during 50 m maximal sprint-running. Fifteen sub-elite male sprinters performed sprints with and without WR over 50 m of in-ground force platforms in a randomised order. A paired t-test was used to determine statistical differences ($p < 0.05$), with effect sizes (ES) calculated between conditions over steps: 1-4, 5-14, and 15-23. WR resulted in small increased 10 m and 50 m sprint times (1.0%, ES = 0.31, 0.9%, ES = 0.44, respectively, $p > 0.05$) compared to the unloaded sprint condition. For spatio-temporal variables, the WR condition resulted in moderate ES changes in step frequency (-2.8%, ES = -0.53, steps 5-14, $p > 0.05$), and contact time (2.5%, ES = 0.57, steps 5-14, and 3.2%, ES = 0.51, average of 23 steps, $p > 0.05$), while step length was unaffected during all step phases of the sprint (ES = 0.02-0.07, $p > 0.05$). Regarding kinetics, during steps 5-14, WR resulted in a moderate decrease (-4.8%, ES = -0.73, $p < 0.05$) in net anterior-posterior impulses and a moderate decrease in vertical stiffness (-5.7%, ES = -0.57, $p > 0.05$). For athletes seeking to overload step frequency and develop anterior-posterior impulse during mid to late accelerated sprinting, WR enables the application of a sprint-specific form of resistance training to be completed without decreasing step length.

Chapter 7.

Macadam, P., Cronin, J.B., Nagahara, R., Zois, J. Uthoff, A., Tinwala, F., Diewald, S., Neville, J. Thigh loaded wearable resistance increases sagittal plane rotational work of the thigh resulting in slower 50 m sprint times. Sports Biomechanics Journal. doi: 10.1080/14763141.2020.1762720

Abstract (240)

The purpose of this study was to determine the acute changes in sagittal plane rotational work of the thigh when wearable resistance (WR) of 2% body mass was attached distally to the thighs during 50 m sprint-running. Fourteen sprint trained athletes (21.4 ± 2.5 years; 100 m best times 11.4 ± 0.5 s) completed two maximum effort sprints with, and without, WR in a randomised order. Sprint times were measured via timing gates set at 10 m and 50 m. Rotational kinematics were obtained over three phases (steps 1-2, 3-6 and 7-10) via inertial measurement unit attached to the left thigh. Quantification of thigh angular displacement (range of motion) and peak thigh angular velocity was subsequently derived to measure rotational work. The WR condition was found to increase sprint times at 10 m (1.4%, effect size [ES] 0.38, p 0.06) and 50 m (1.9%, ES 0.55, p 0.04) compared to the unloaded condition. The WR condition resulted in trivial to small increases in angular displacement of the thigh during all phases (0.6-3.4%, ES 0.04-0.26, $p > 0.05$). A significant decrease in angular velocity of the thigh was found in all step phases (-2.5% to -8.0%, ES 0.17-0.51, p 0.00-0.04), except extension in step phase 1 with the WR. Rotational work was increased (9.8-18.8%, ES 0.35-0.53, $p < 0.00$) with WR in all phases of the sprint. Thigh attached WR provides a means to significantly increase rotational work specific to sprinting.

Chapter 8.

Macadam, P., Nuell, S., Cronin, J.B., Diewald, S., Neville, J. (2019). Thigh positioned wearable resistance improves 40 m sprint performance: a longitudinal single case design study. Journal of Australian Strength & Conditioning. 27(4), 39-45.

Abstract (216 words)

Lower limb wearable resistance (WR) can be used to provide rotational overload to the limbs, changing the limb's inertial properties which may potentially modify sprint-running mechanics. Therefore, the purpose of this study was to determine how thigh positioned WR of 2% body mass affected 40 m sprint-running performance following a 5 week training protocol. One male former sprinter (32 years, 72.4 kg and 180.2 cm, 10.90 s 100 m time) undertook a 5 week periodised sprint-training protocol with WR. Inertial measurement units, radar and a high-speed camera were used to measure the variables of interest. Pre and post measures during sprint performance were statistically analysed via the ±2 x SD band method to identify substantial changes. Substantially faster times were found at all distances of 10 m (-3.4%), 20 m (-2.5%), 30 m (-2.4%), and 40 m (-2.4%). Theoretical maximum velocity (1.2%), theoretical measures of horizontal force (7.1%) and maximum power (8.4%) were all substantially increased. Contact times were substantially decreased (-5.5%), while flight times (4.7%) and vertical stiffness (12.9%) were substantially increased. WR provides a promising sprint specific training means for rotational overload and subsequent speed adaption with increased horizontal force and power production resulting in faster times during accelerated sprint-running. Future research is needed with a larger cohort to verify the findings of this case study.

Appendix IV. Additional Related Research Outputs Since Starting the Doctor of Philosophy

Peer-Reviewed Journal Publications

Simperingham, K., Cronin, J., Ross, A., Brown, S**., Macadam, P.,** Pearson, S. (2020). Acute changes in acceleration phase sprint biomechanics with lower body wearable resistance. *Sports Biom.* doi: 10.1080/14763141.2020.1743349.

Uthoff, A., Cronin, J., **Macadam, P.,** Nagahara. R., Graham, S., Tinwala. F, Neville, J. (2020). Effects of forearm wearable resistance on acceleration mechanics in collegiate track sprinters. *Eur J Sport Sci.* doi: 10.1080/17461391.2020.1722256.

Macadam, P., Mishra, M., Feser, E., Uthoff, A., Cronin, J., Zois, J., Nagahara. R., Tinwala. F. (2019). Force-velocity profile changes with forearm wearable resistance during standing start sprinting. *Eur J Sport Sci.* doi: 10.1080/17461391.2019.1686070.

Fielding, A, Gill, N, **Macadam, P.,** Plews, D. (2019). Acute metabolic changes with thigh positioned wearable resistance during submaximal running in endurance trained runners. *Sports, 7*(8), doi: 10.3390/sports7080187.

Macadam, P., Chau, A., Cronin, J. (2019). Wearable resistance acutely enhances club head speed in skilled female golfers. *Int J Sports Sci Coach. 14(*5), 675-680. doi: 10.1177/1747954119863882.

Feser, E., **Macadam, P.,** Cronin, J. (2019). The effects of lower limb wearable resistance on sprint-running performance: a systematic review. *Eur J Sport Sci,* doi: 10.1080/17461391.2019.1629631.

Macadam, P., Cronin, J., Feser, E. (2019). The effects of weighted vests on sprint-running performance: a systematic review. *Sports Biomech,* doi: 10.1080/14763141.2019.1607542.

Dolchetti, J, Cronin, J., **Macadam, P.,** Feser, E. (2019). Wearable resistance training for speed and agility. *Strength Cond J, 41*(4), 105-111. doi: 10.1519/SSC.0000000000000436

Couture, G., Simperingham, K., Cronin, J., Lorimer, A., Kilding, A., & **Macadam, P.,** (2018). Running with wearable resistance: acute effects on the spatiotemporal and kinetic characteristics of submaximal running. *Sports Biomech,* doi: 10.1080/14763141.2018.1508490.

Macadam, P., Simperingham, K., Cronin, J., (2018). Sprint running acceleration performance with forearm wearable resistance. *J Sci Med Sport, 22*(3), 348–352. doi: 10.1016/j.jsams.2018.08.012.

Marriner, C.R., Cronin, J.B. **Macadam, P.,** & Storey, A. (2018). The effect of wearable resistance on power cleans in recreationally trained males. *Australian J Strength & Cond*, 26 (3), 22-26.

Conference Presentation

Feser, E., **Macadam, P.,** Ngarahra, R., & Cronin, J. (2018). The effects of lower limb wearable resistance on step kinematics during sprint running. *Proceedings of the 36th International Conference of Biomechanics in Sports.* (pp. 114-117). Auckland, New Zealand: International Society of Biomechanics in Sports.